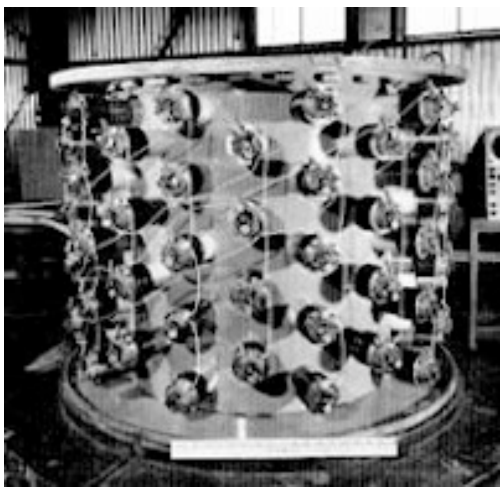
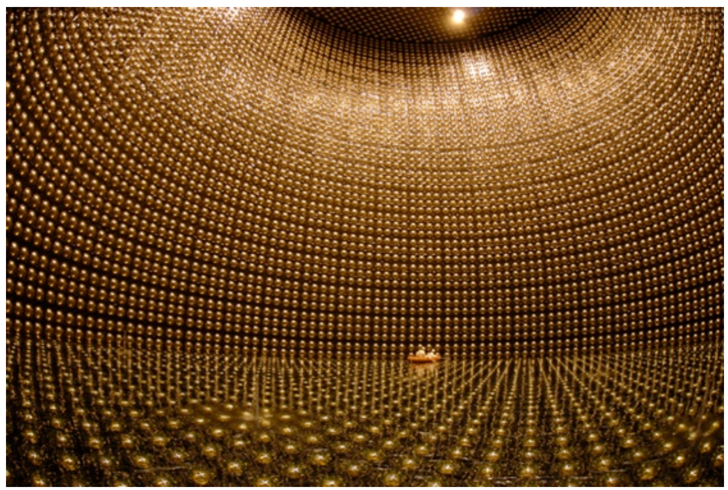
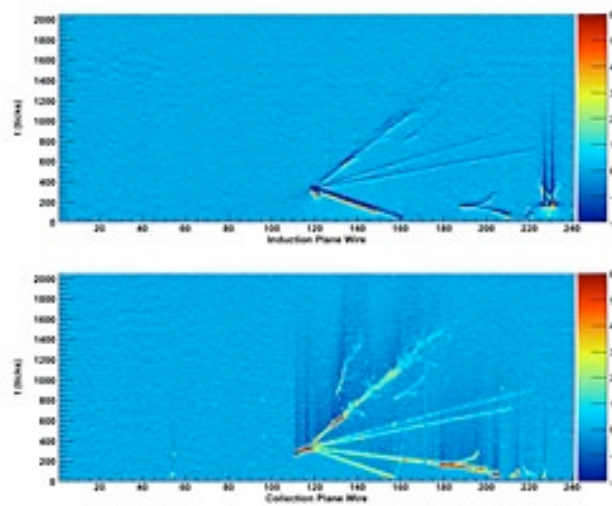
Detectors in Neutrino Physics

Karsten M. Heeger

University of Wisconsin







FNAL, February 16, 2012

Disclaimer & Acknowledgements

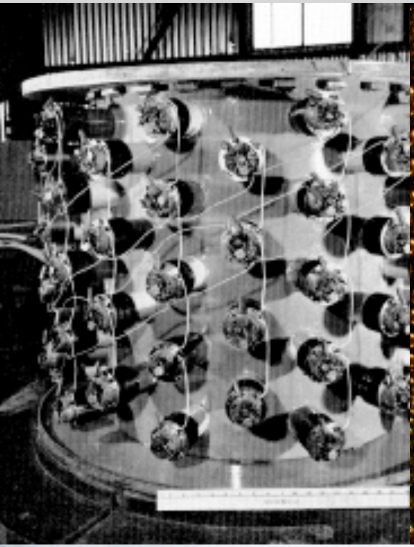
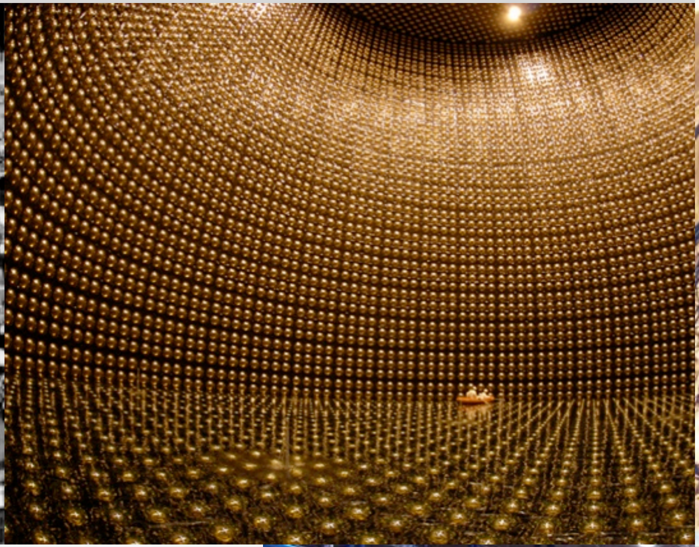
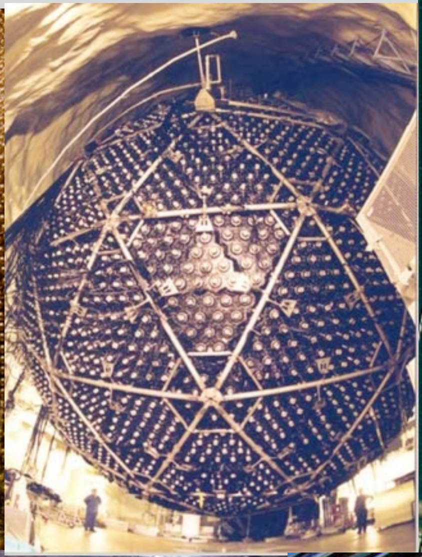
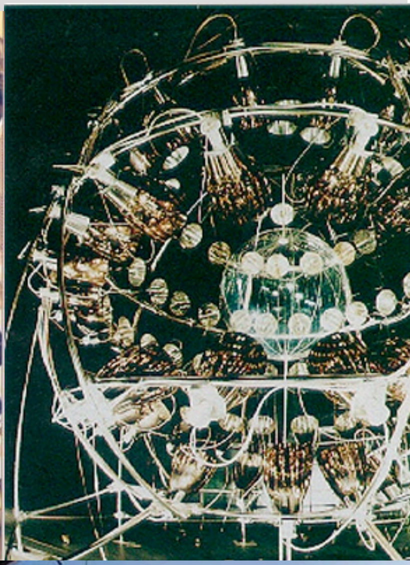
- Disclaimer
  - Cannot show or explain every neutrino detector. This will be a selection of detectors and their principles.
  - Will try to convey principles and important considerations in detector design and neutrino measurements.

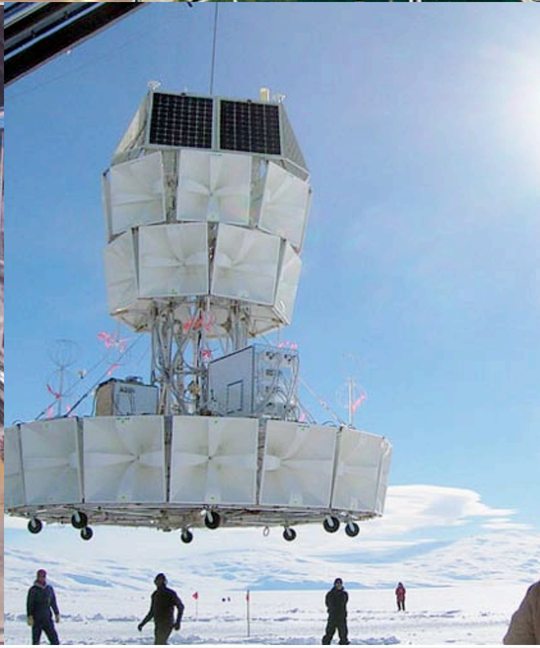
- Acknowledgements
  - slides and information from talks given at NNSS2009, NuFact2010, Neutrino 2010, WIN11, NeuTEL 2011, and TIPP2011

Outline

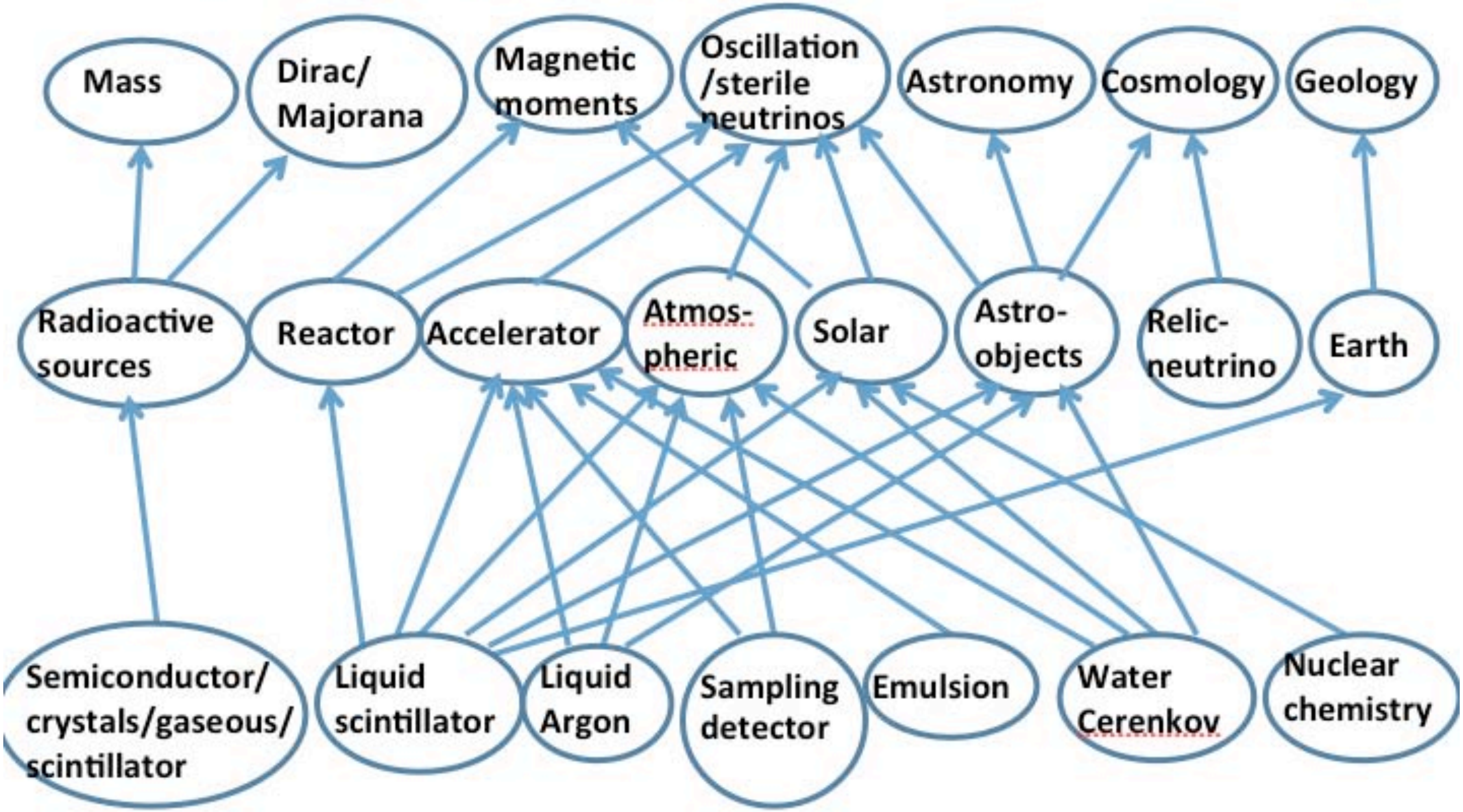
- world of neutrino detectors
- neutrino sources
- historical perspective
  - lessons from the pioneers
- neutrinos as a probe - probing neutrinos
- experimental challenges
  - cross-sections
  - detector segmentation and backgrounds
- detectors in neutrino physics
  - detection channels
  - particle signatures
  - present and future

A World of Neutrino Detectors

Neutrino physics：problems and methods



Y. Wang

Neutrinos from the Big Bang ~330 neutrinos per cm^3

Supernova Neutrinos

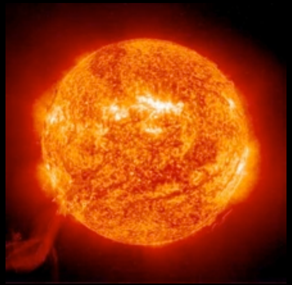
Atmospheric Neutrinos

High Energy Cosmic Neutrinos

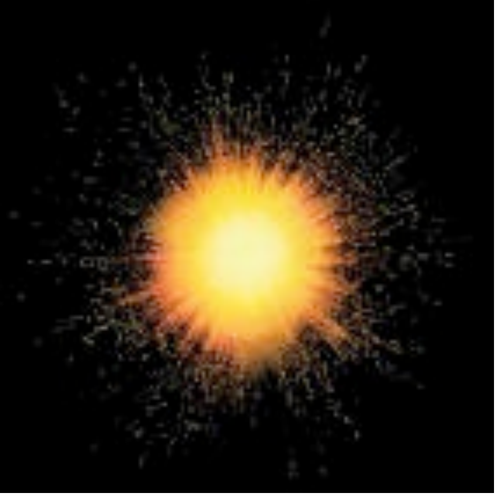
Geo Neutrinos

Accelerator&Reactor Neutrinos

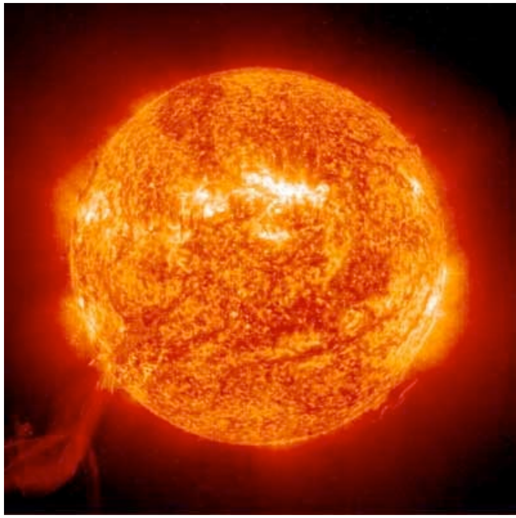
Solar Neutrinos



Neutrino Energies



Big-Bang neutrinos ~ 0.0004 eV



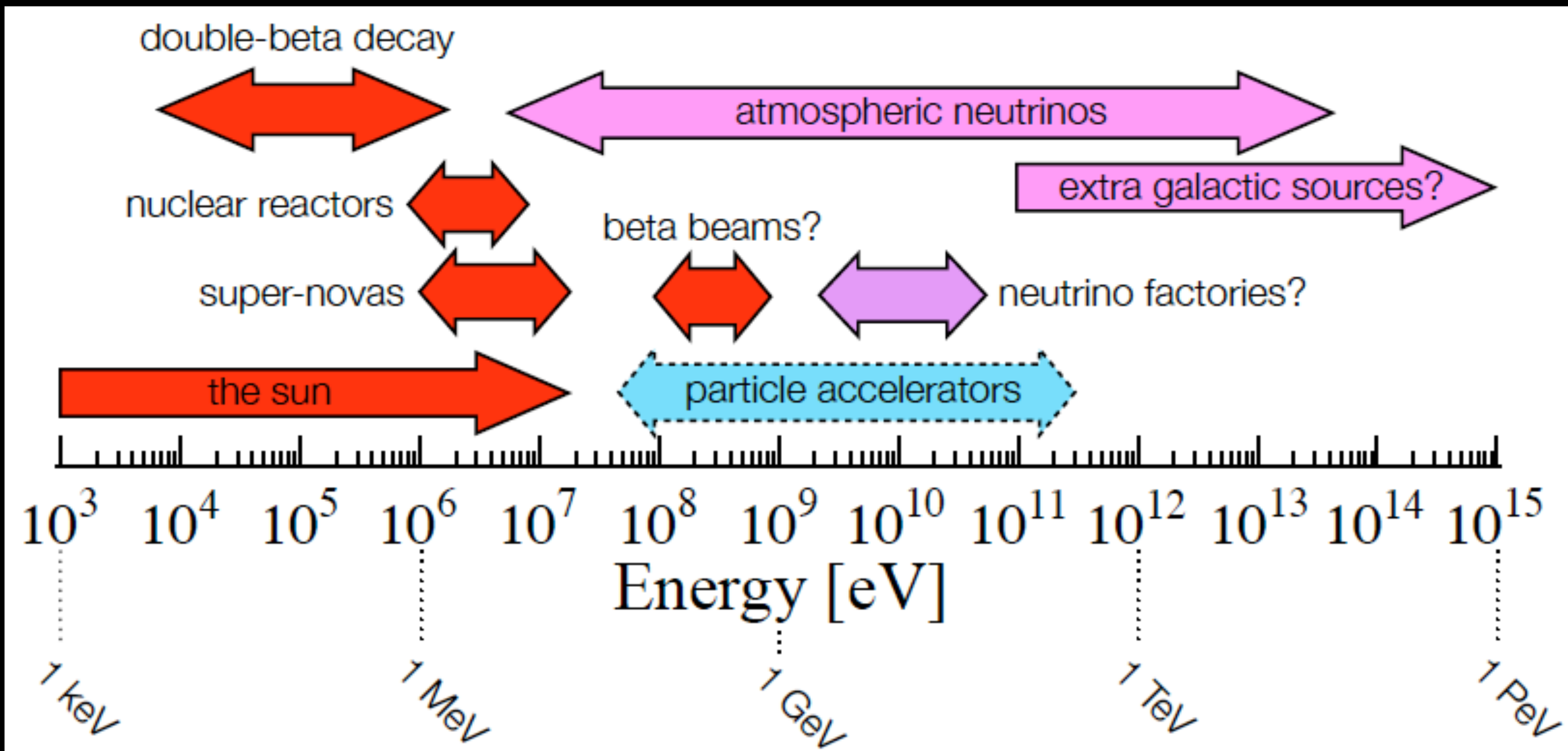
Neutrinos from the Sun < 20 MeV
depending of their origin.

Atmospheric neutrinos ~ GeV

Antineutrinos from nuclear reactors < 10.0 MeV

Neutrinos from accelerators up to GeV (10^9 eV)

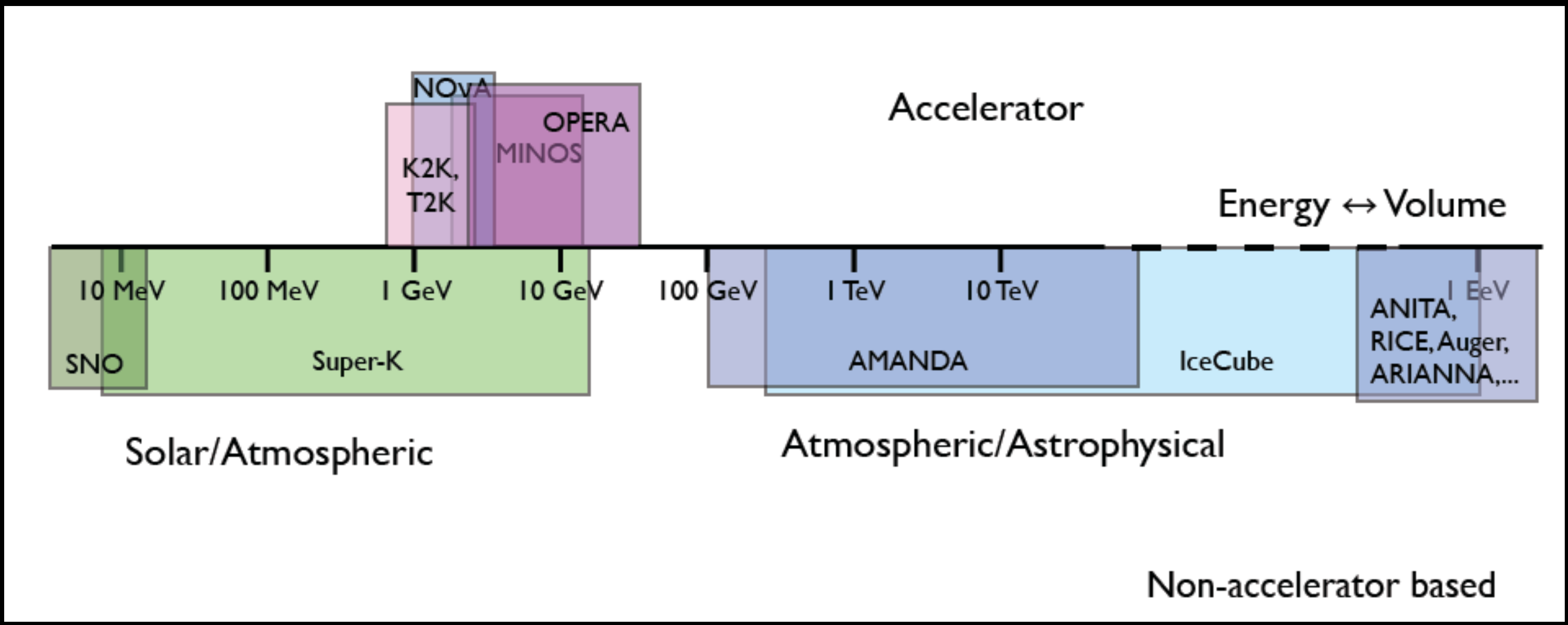
Neutrino Energy Spectrum



M. Messier

detectors must match requirements of ν source

Neutrino Detector Spectrum

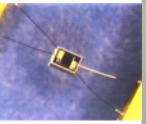


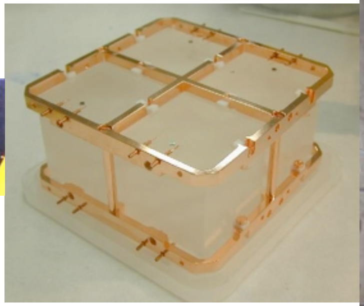
D. Grant

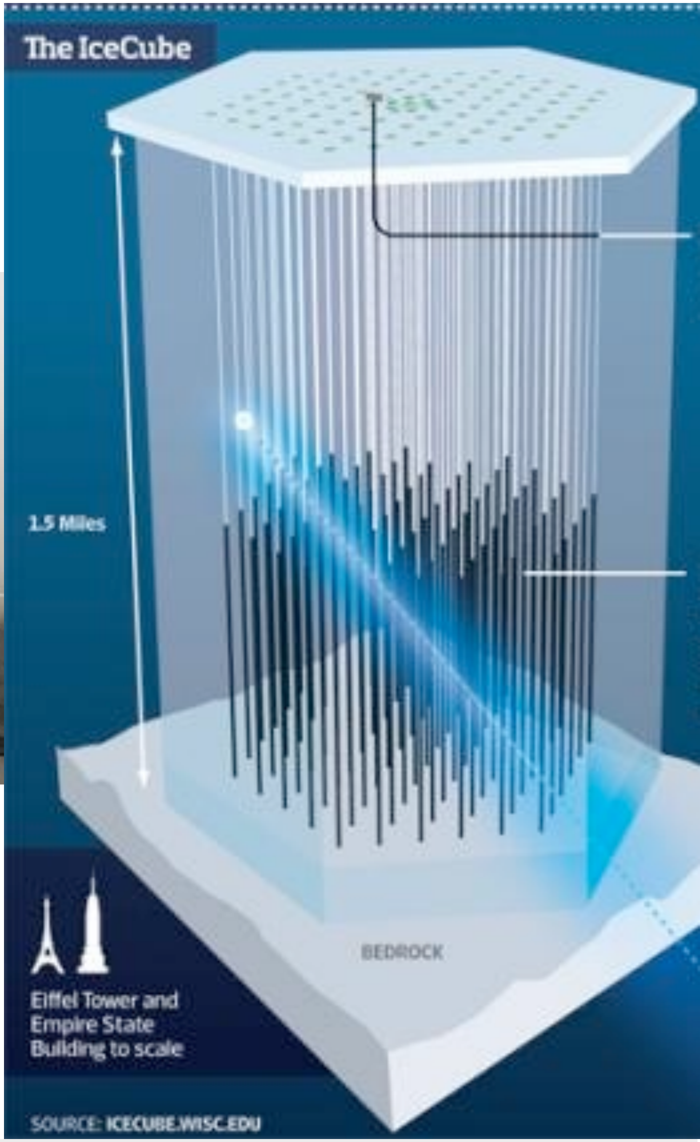
energy - volume correspondence

Neutrino Detector Spectrum

from the very small to the very big





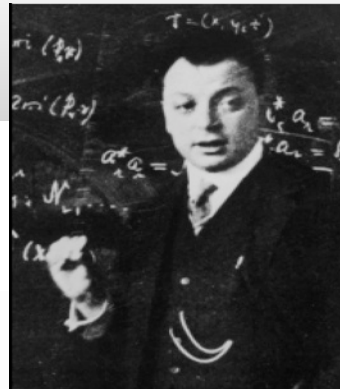


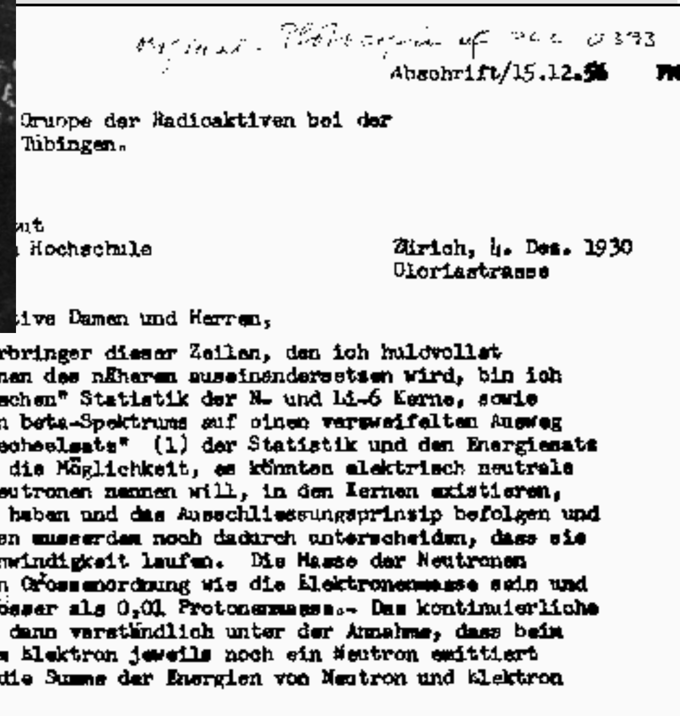
energy - volume correspondencce

Historical Perspective: Lessons from the Pioneers

Postulate of the Neutrino

Pauli, 1930





Abschrift/15.12.56

Gruppe der Radioaktiven bei der
Tübingen.

ut
Hochschule

Zürich, 4. Des. 1930
Gloriastrasse

ive Damen und Herren,

Wie der Ueberbringer dieser Zeilen, den ich huldvollst anzuhören bitte, Ihnen des näheren auseinandersetzen wird, bin ich angesichts der "falschen" Statistik der N- und Li-6 Kerne, sowie des kontinuierlichen beta-Spektrums auf einen verzweifelten Ausweg verfallen um den "Wechselsatz" (1) der Statistik und den Energiesatz zu retten. Nämlich die Möglichkeit, es könnten elektrisch neutrale Teilchen, die ich Neutronen nennen will, in den Kernen existieren, welche den Spin 1/2 haben und das Ausschliessungsprinzip befolgen und sich von Lichtquanten ausserdem noch dadurch unterscheiden, dass sie nicht mit Lichtgeschwindigkeit laufen. Die Masse der Neutronen müsste von derselben Grossenordnung wie die Elektronenmasse sein und jedenfalls nicht grösser als 0,01 Protonenmasse.- Das kontinuierliche beta- Spektrum wäre dann verständlich unter der Annahme, dass beim beta-Zerfall mit dem Elektron jeweils noch ein Neutron emittiert wird, derart, dass die Summe der Energien von Neutron und Elektron konstant ist.

Chadwick, 1914

$N \rightarrow N' + e^-$ some nuclei emit electrons!

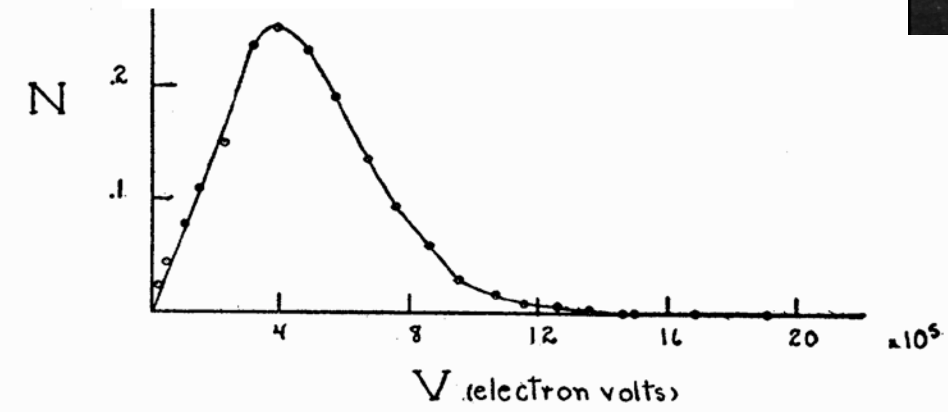
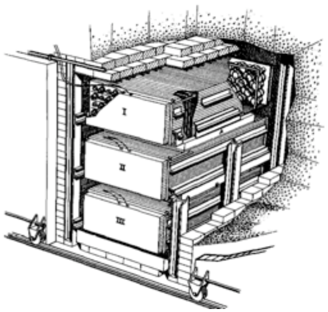


FIG. 5. Energy distribution curve of the beta-rays.

Reines and Cowan, 1956
"Observation of the Free Antineutrino"

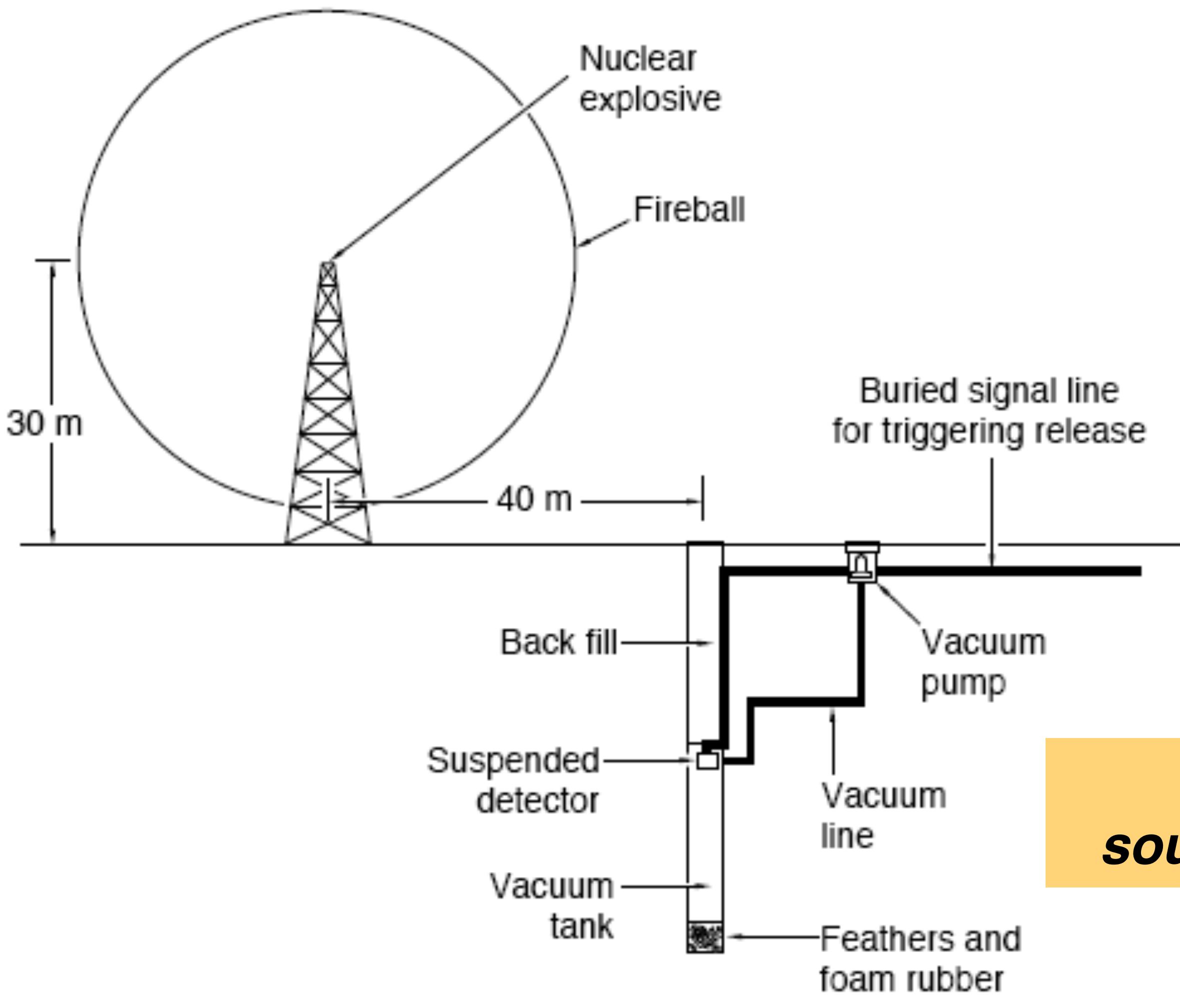


inverse beta decay

$\overline{\nu}_e + p \rightarrow e^+ + n$

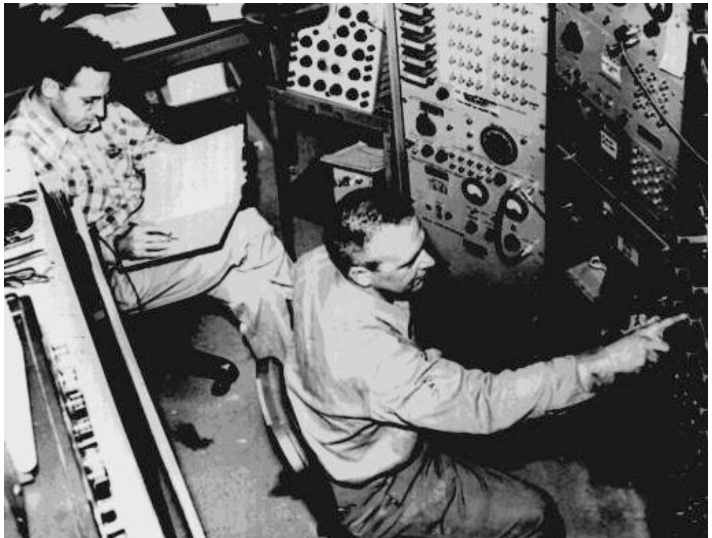
Be patient. It is hard and takes a long time.

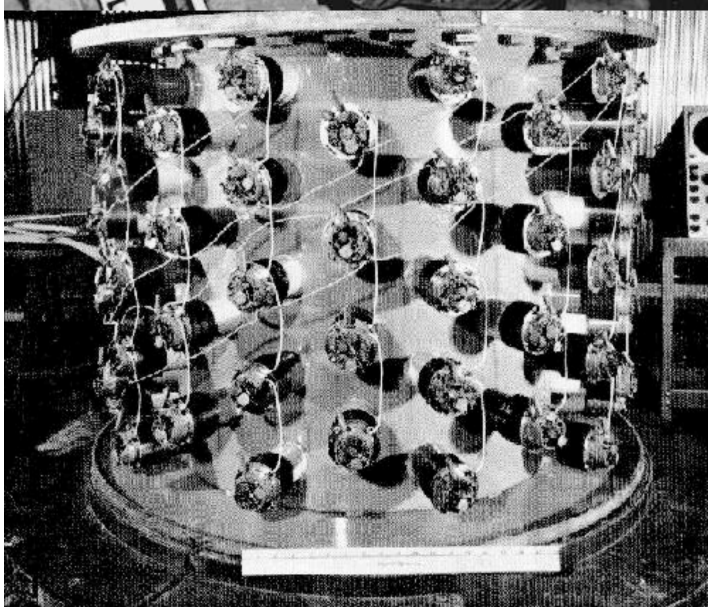
First Proposal For Direct Detection of Neutrino

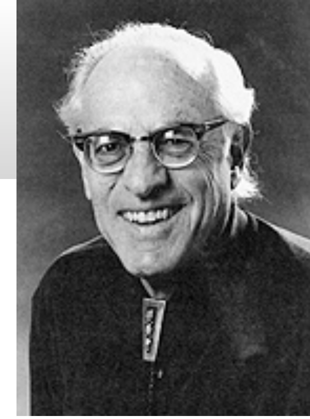


Need an intense source of neutrinos

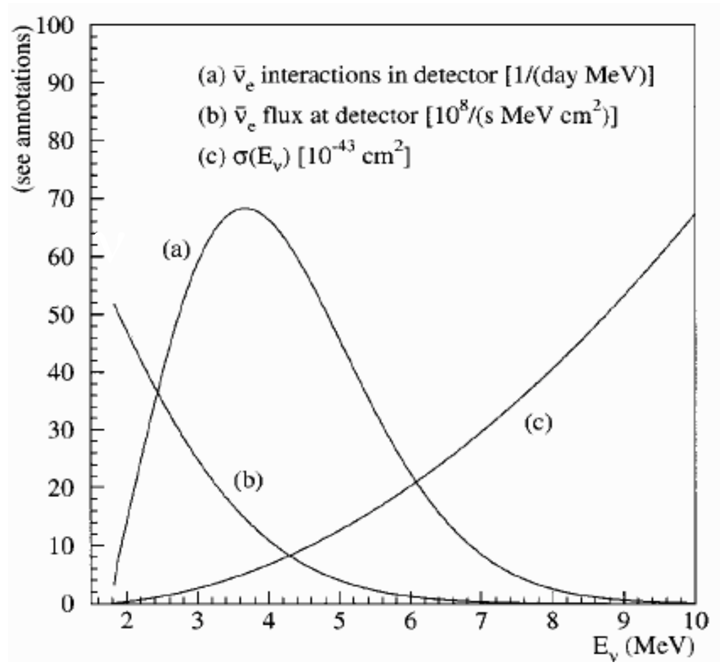
First Antineutrino Detector



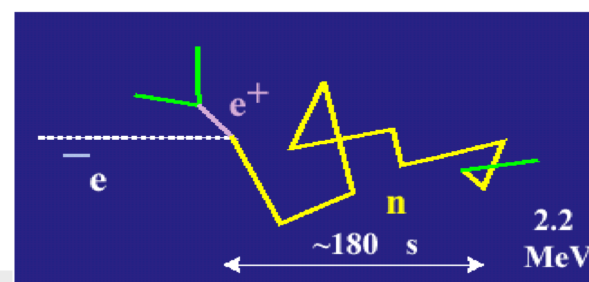




Reines and Cowan 1956

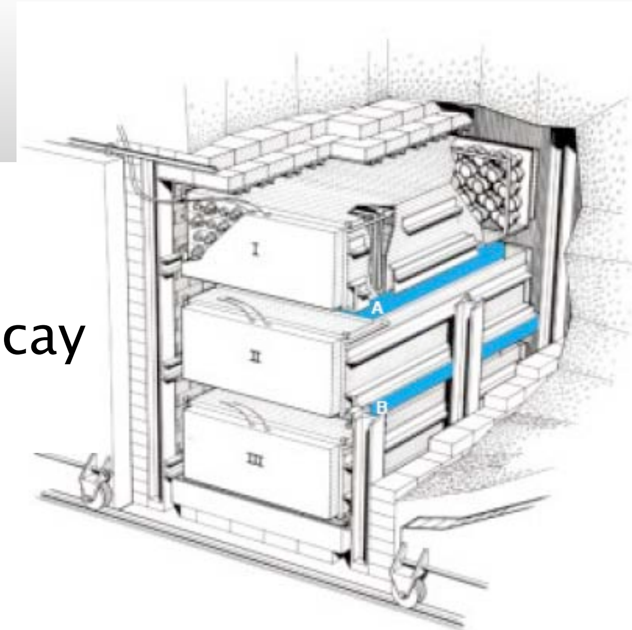


$$\bar{\nu}_e + p \rightarrow e^+ + n$$



Observation of the Free Antineutrino

1959 The Savannah River Detector - A new design

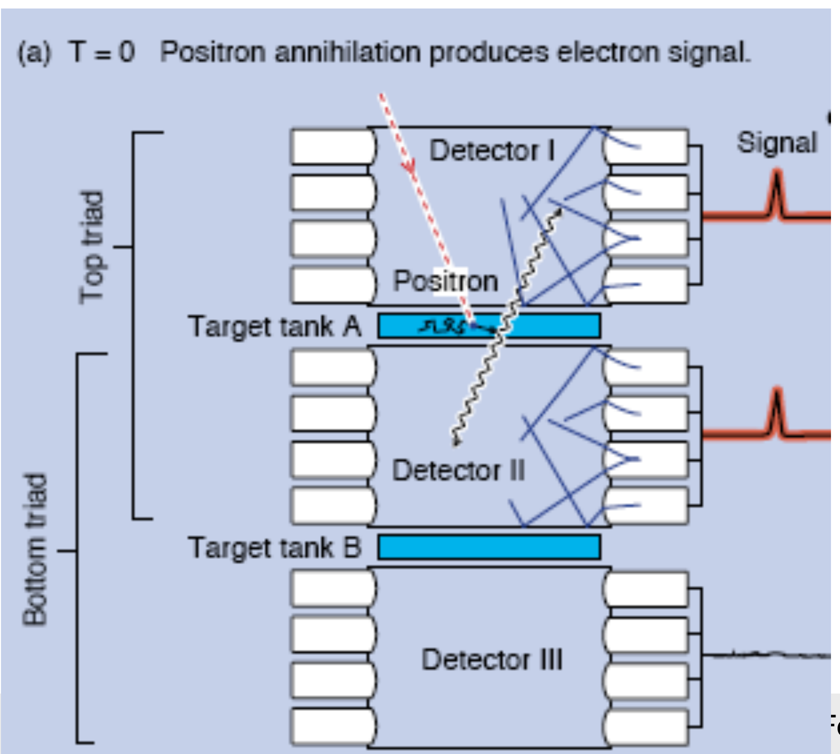


Backgrounds!
Second version of Reines' experiment worked!

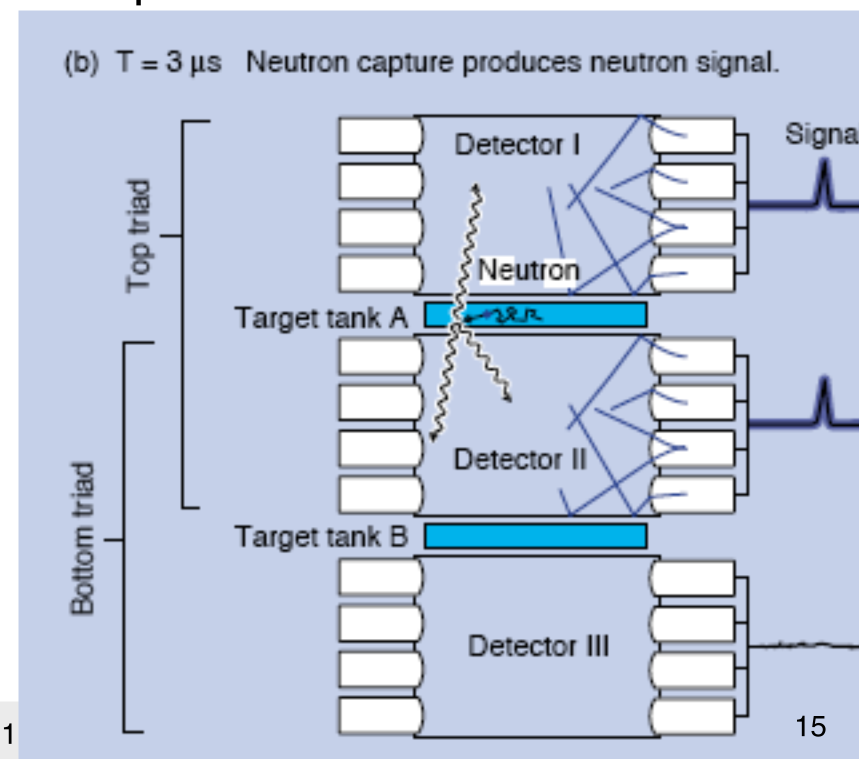
inverse beta decay

$$\bar{\nu}_e + p \rightarrow e^+ + n$$

positron annihilation

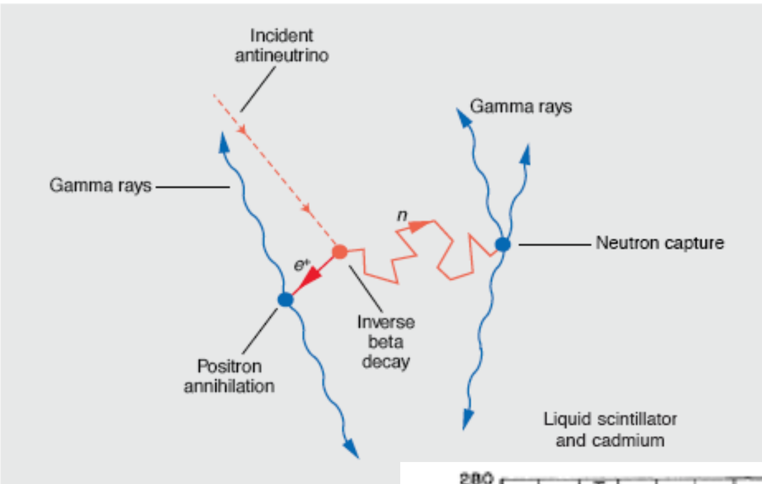


n capture

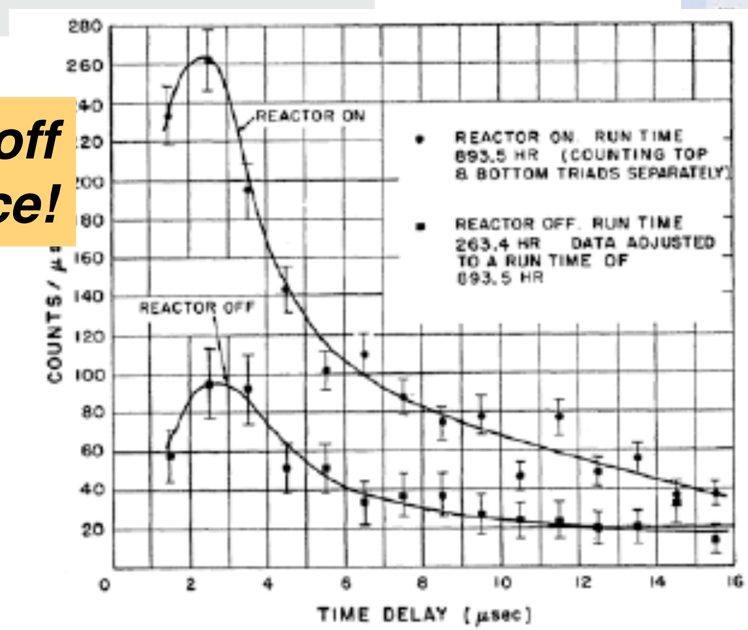


Reines-Cowan Experiment

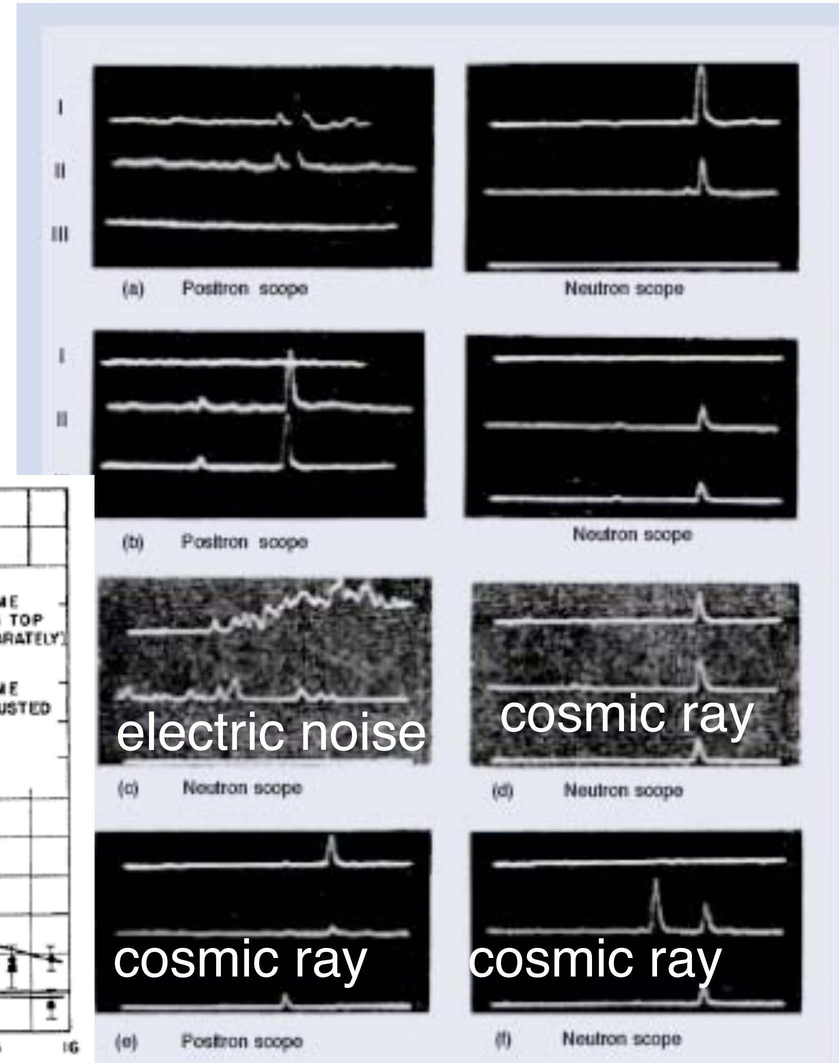
coincidence event signature



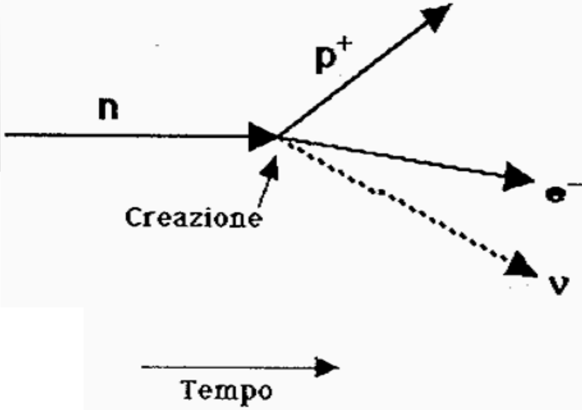
Ideal to turn off neutrino source!



event signal

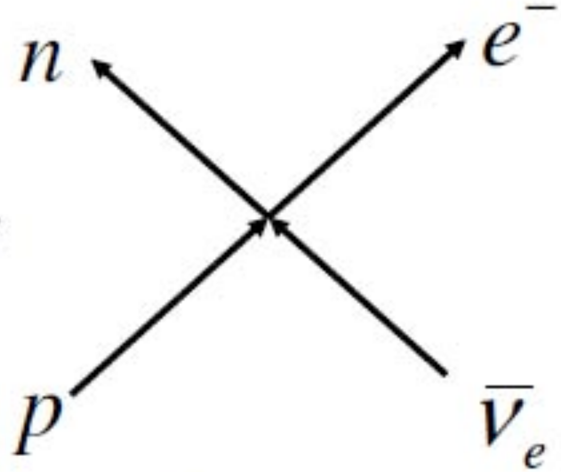


Fermi’s Theory of Beta Decay



existence of a point-like four fermion interaction

$$n \to p + e^- + \nu_e$$



Lagrangian of the interaction:

$$L(x) = -\frac{G_F}{\sqrt{2}}\left[\bar{\phi}_p(x)\gamma^\mu \phi_n(x)\right]\left[\bar{\phi}_e(x)\gamma_\mu \phi_\nu(x)\right]$$

G_F = Fermi coupling constant = $(1.16637 \pm 0.00001)\times 10^{-5}\ GeV^{-2}$

ANNO IV - VOL. II - N. 12 QUINDICINALE 31 DICEMBRE 1933 - XII

LA RICERCA SCIENTIFICA

ED IL PROGRESSO TECNICO NELL'ECONOMIA NAZIONALE

Tentativo di una teoria dell'emissione dei raggi "beta"

Nota del prof. ENRICO FERMI

Riassunto: Teoria della emissione dei raggi β delle sostanze radioattive, fondata sull'ipotesi che gli elettroni emessi dai nuclei non esistano prima della disintegrazione ma vengano formati, insieme ad un neutrino, in modo analogo alla formazione di un quanto di luce che accompagna un salto quantico di un atomo. Confronto della teoria con l'esperienza.

Fermi’s theory still stands (parity violation added in the 50s).

Fermi’s Idea for Measuring m_ν

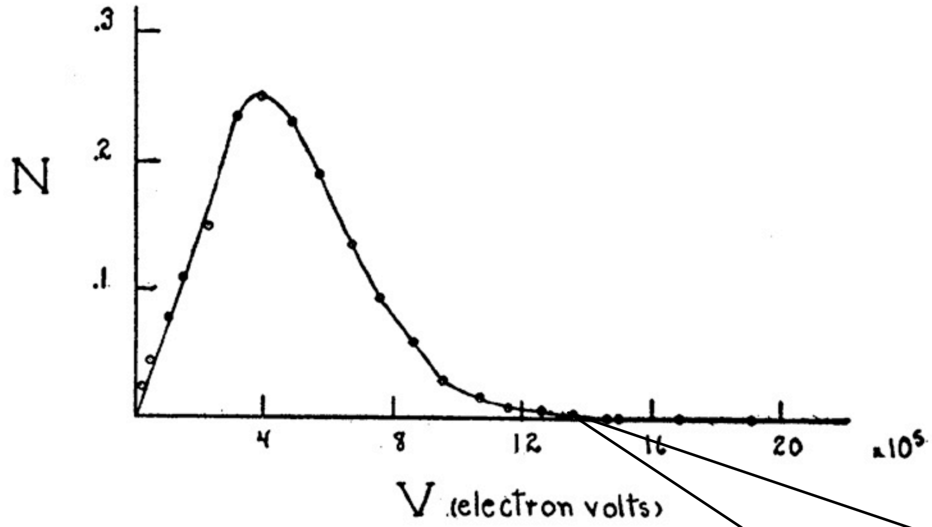


FIG. 5. Energy distribution curve of the beta-rays.

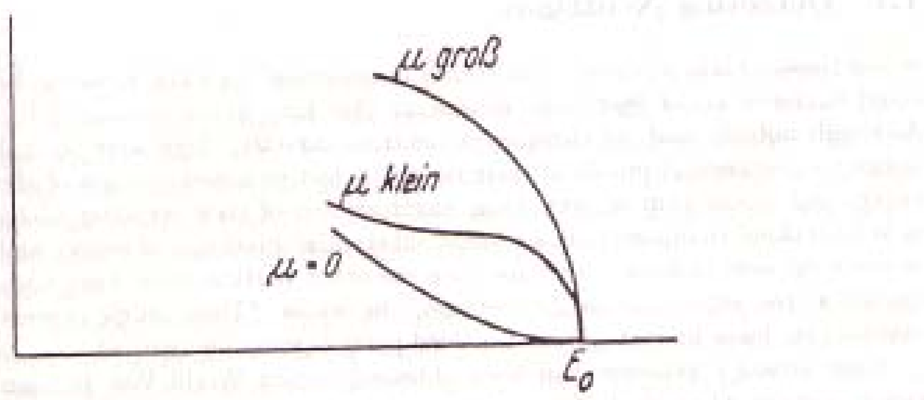
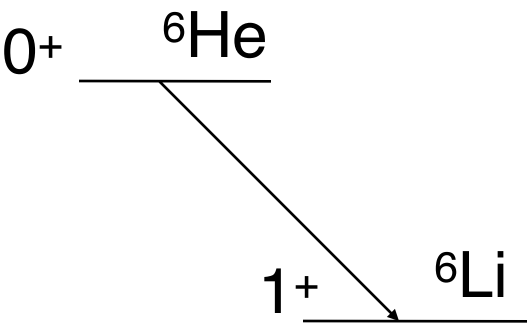


Fig. 1.2. Graph from Fermi's famous paper on the theory of beta decay, showing how the shape of the emitted electron's energy spectrum varies with neutrino mass

Beta Decay



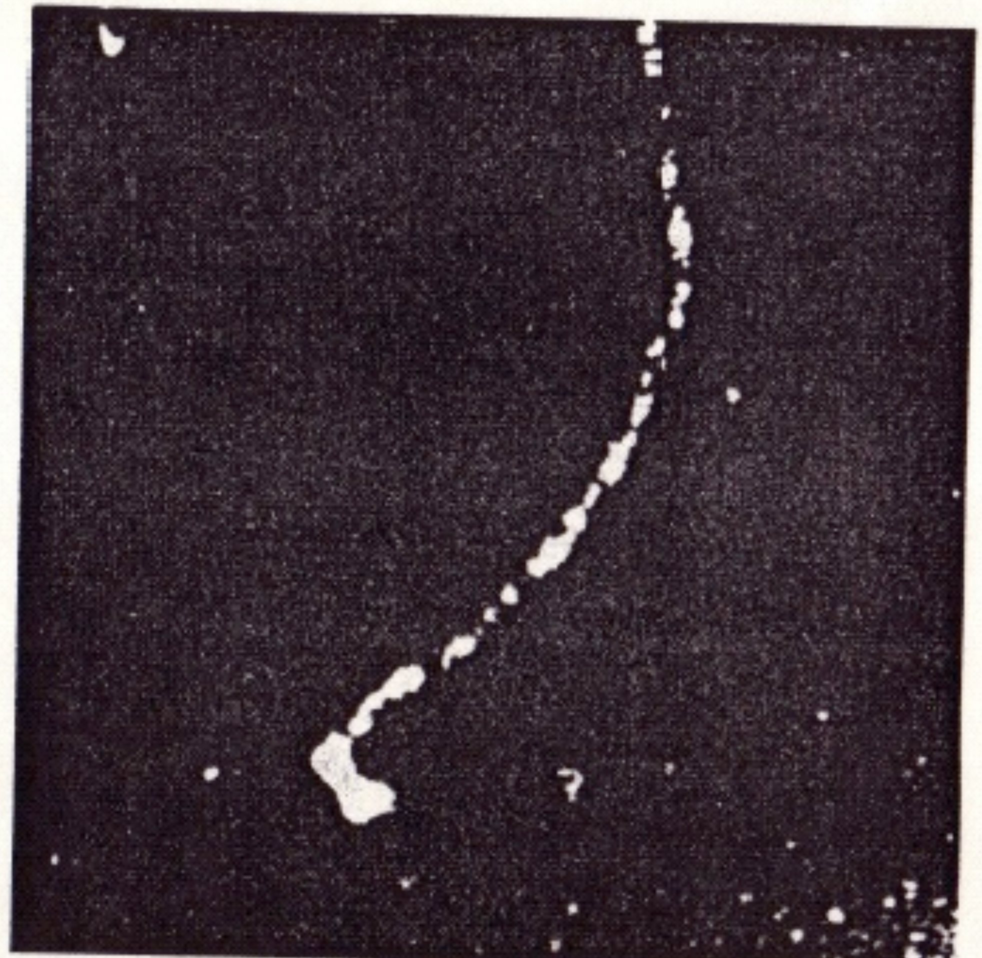


Fig. 1.2. Cloud chamber picture of the decay of He^6 (CSIKAI *et al.* [1958]).

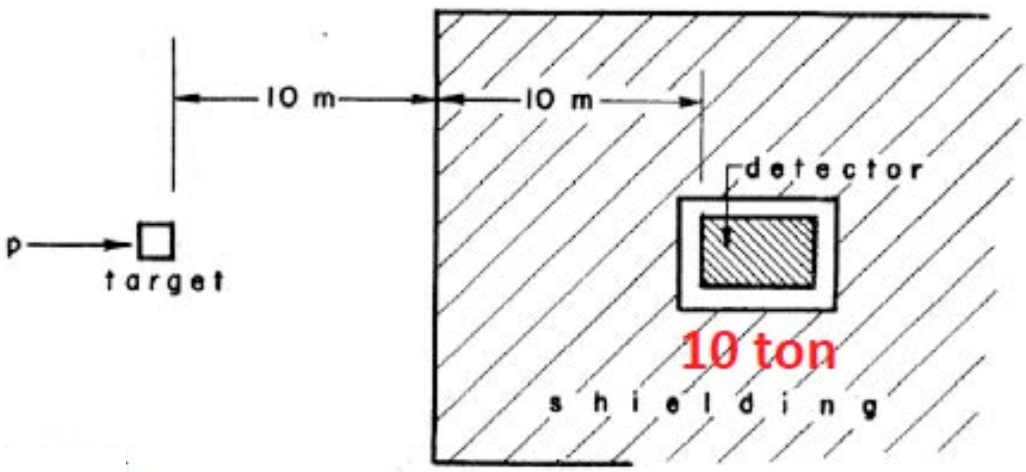
imaging events

$$^6He \rightarrow {}^6Li + e^- + \nu$$

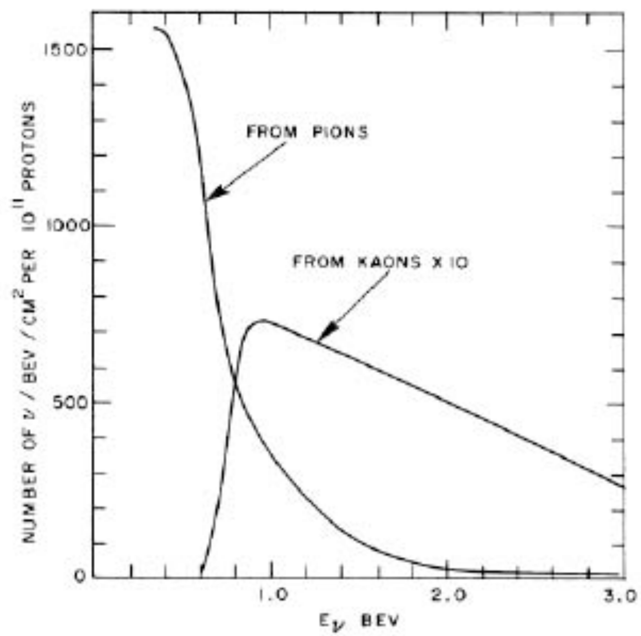
Neutrinos from Accelerators

High energy ν from accelerators to study weak interactions

M. Schwartz, Phys. Rev. Lett. 4 (1960) 306



ν's from π and K decays

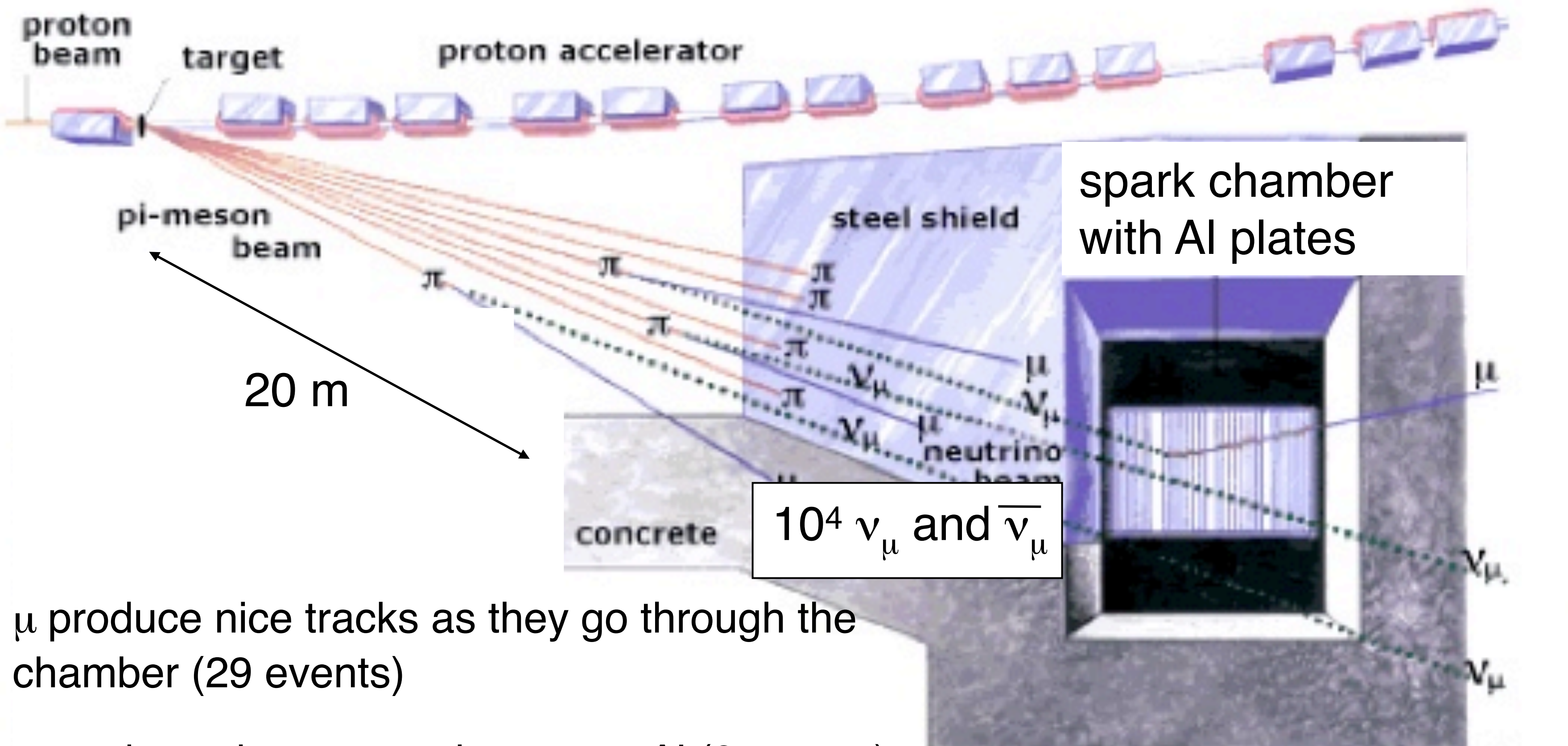


Discovery of Muon Neutrino

Lederman, Schwartz, Steinberger

1962

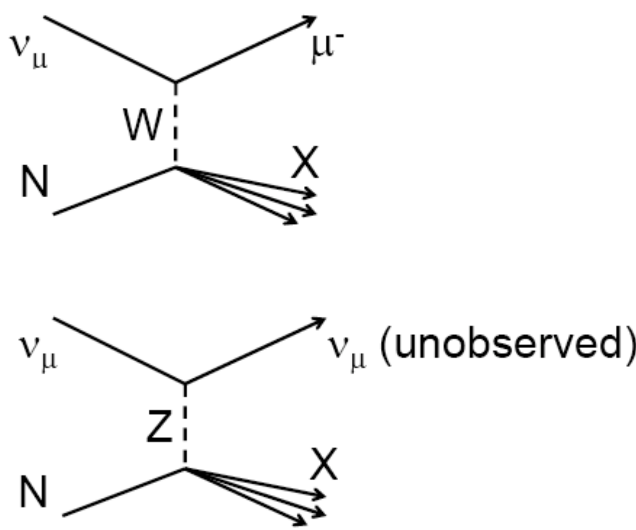
$$\bar{\nu}_\mu + p \rightarrow n + \mu^+$$
$$\nu_\mu + n \rightarrow p + \mu^-$$

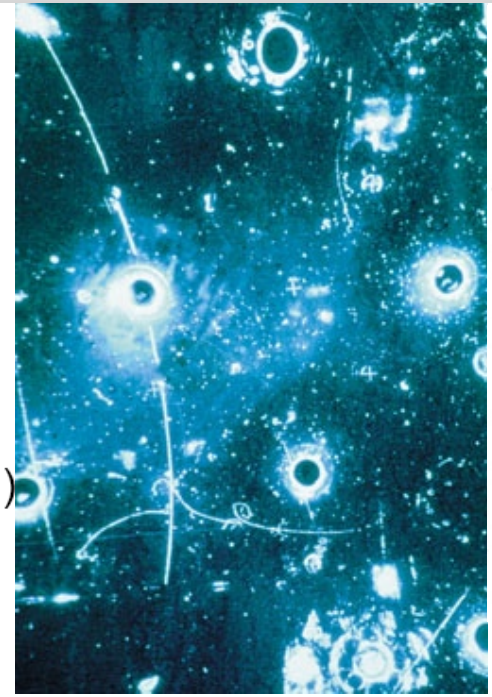


μ produce nice tracks as they go through the chamber (29 events)

e produce showers as they cross Al (0 events)

Neutral Current Discovery (1973)





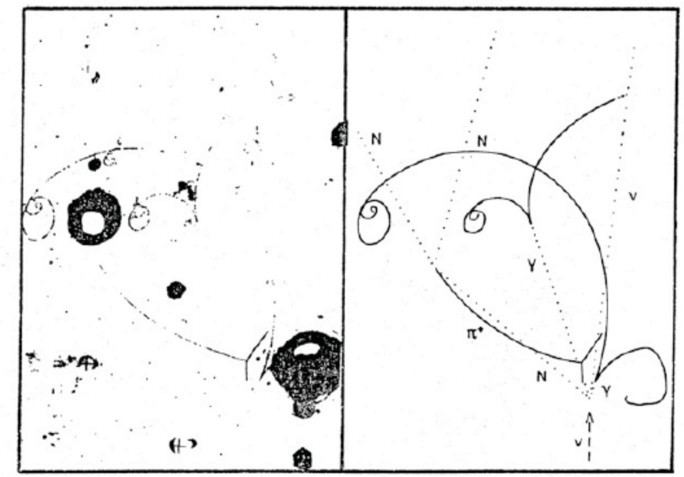


Abb. 15: Ein Kandidat für die Reaktion ($\nu n \rightarrow \nu n \pi^0$). Im Gegensatz zum Normalfall wird das Neutron durch inelastische Reaktion strahlabwärts

Gargamelle bubble chamber at CERN showing how an invisible neutrino has jogged an electron

Major triumph for the Standard Model

Table 1

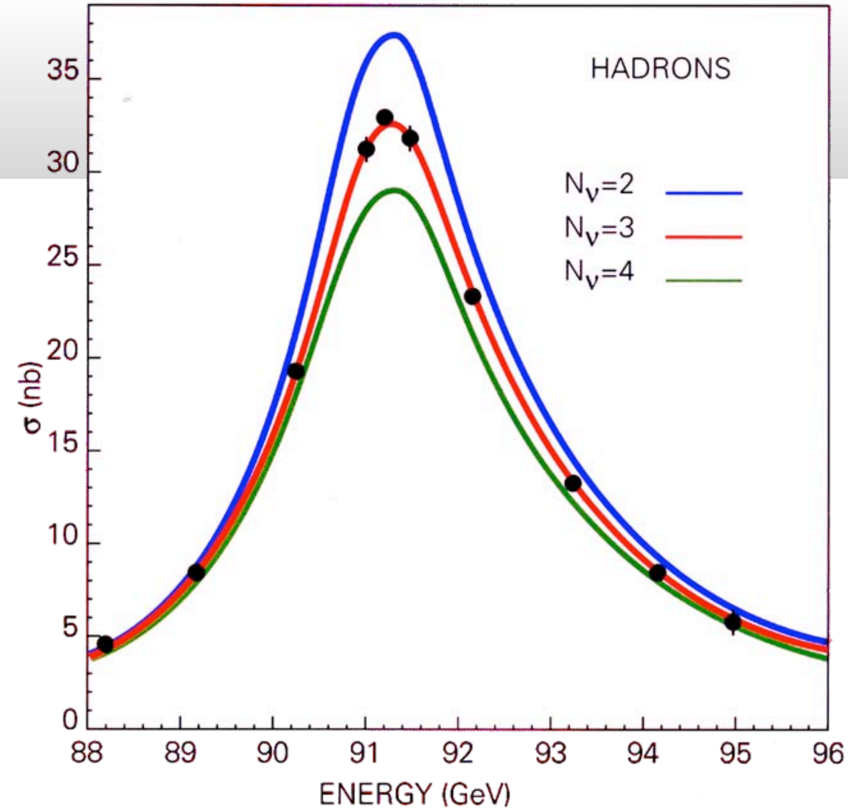
	ν-exposure	ν̄-exposure
No. of neutral-current candidates	102	64
No. of charged-current candidates	428	148

Number of Active Neutrinos

Precision studies of Z-line shape, determine number of active light neutrinos

Each separate $(\nu_{l_i})_L$ adds to total Z-width.

$$Z^o \to q\bar{q}, l\bar{l} \qquad N_\nu = \frac{\Gamma_{\rm inv}}{\Gamma_\ell}\left(\frac{\Gamma_\ell}{\Gamma_\nu}\right)_{\rm SM}$$



From LEP, one finds:

$N_\nu = 2.984 \pm 0.008$

which argues strongly for only having 3 generations

Before ν_τ was detected directly!

Big bang nucleosynthesis gives a constraint on the effective number of light neutrinos at T~ 1 MeV:

$1.2 < N_\nu^{\rm eff} < 3.3$ [99% CL]

Search for tau Neutrino

Discovery of τ lepton at SLAC (Martin Pearl, 1975)

→ there should be a corresponding neutrino.

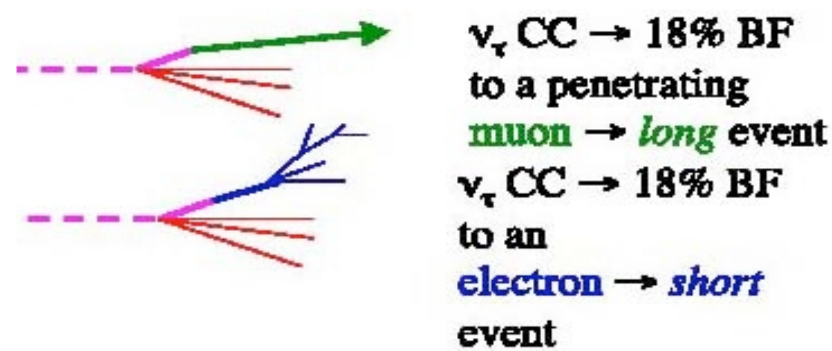
In 1989, indirect evidence for the existence of ν_τ in measurement of Z-width

→ no one had directly observed the tau neutrino.

The tau neutrino interact and form a tau that has an 18% probability of decaying to

- a muon and two neutrinos (long event)
- an electron and two neutrinos (short event)

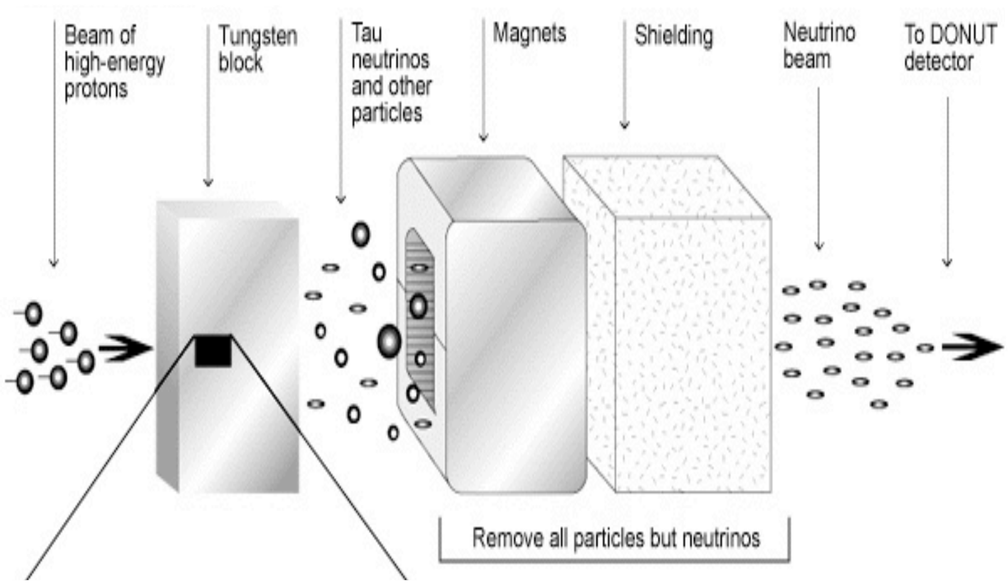
86% of all tau decays involve only 1 charged particle (a kink) which is the particle physicists are looking for in DONUT experiment



Discovery of tau Neutrino

2000

An 800 GeV beam of protons from the TeVatron collides with a block of tungsten



D_s decay into τ and ν_τ neutrino

$$D_s \rightarrow \nu_\tau + \tau$$

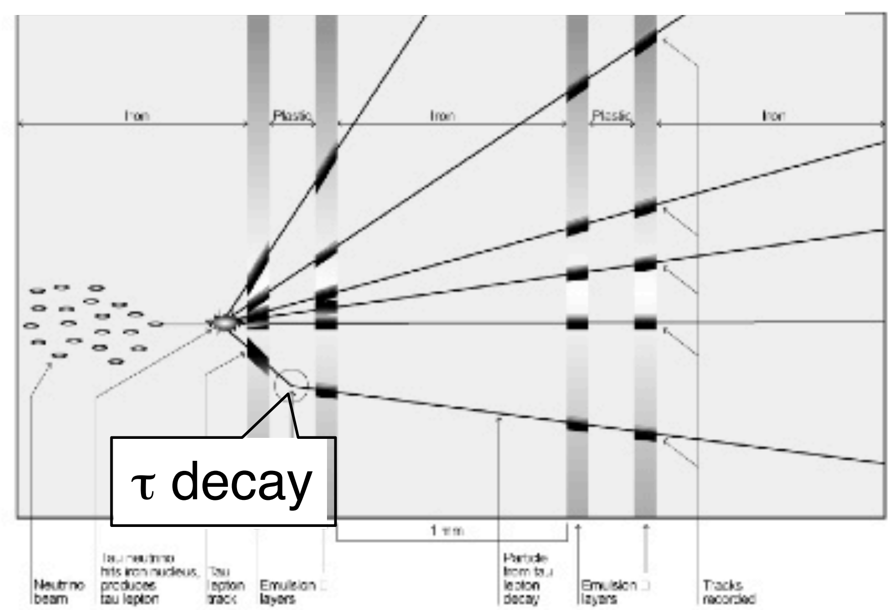
$$\tau \rightarrow \nu_\tau + X$$

Experimental Challenges:

- Very short lifetime of the τ.
- ν_τ is extremely non-interacting

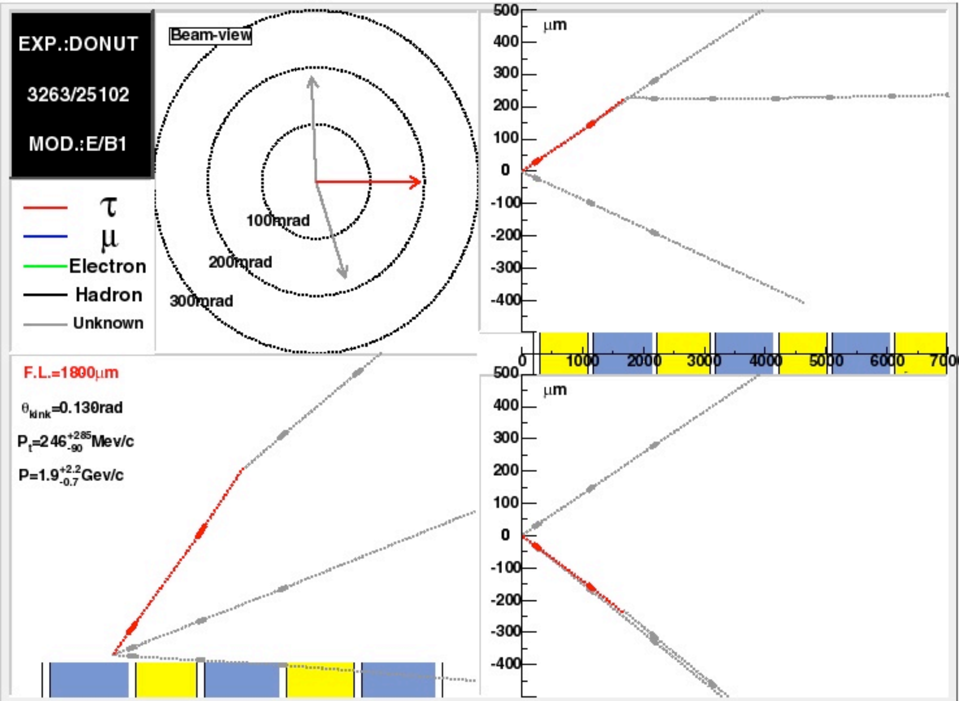
(detector must have a very fine resolution).

Detecting a τ Neutrino

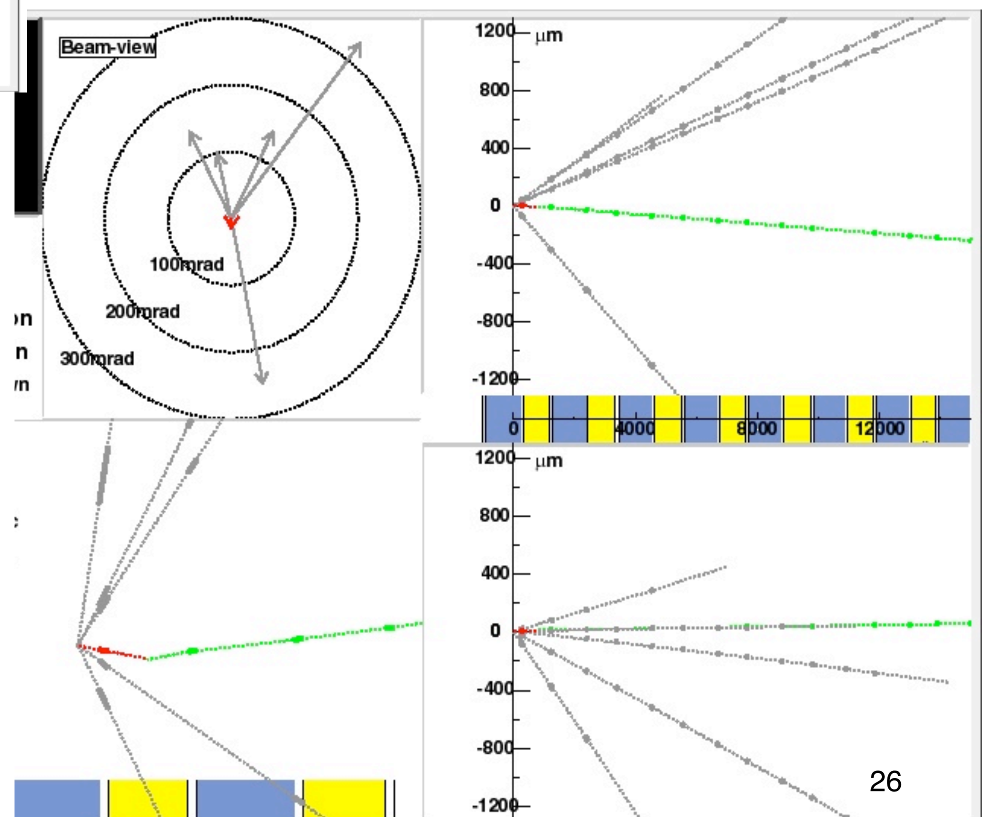


6,000,000 candidate events on tape

4 clean tau events



A ν_τ interacted with a nucleon in a steel layer, producing a τ.



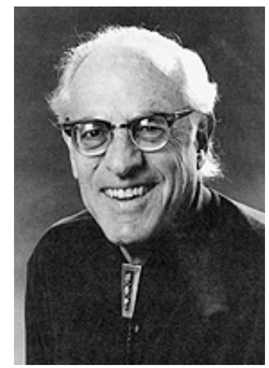
Long tau decay because it decays to one charged particle, the electron, and the decay vertex occurs several sheets downstream from the neutrino interaction vertex.

Short tau decay to an electron in less than the distance it takes to traverse an emulsion layer.

“Standard Model” Neutrino Physics

1914 Electron Spectrum in β decay is continuous

1930 Pauli postulates that a new particle is emitted



1933 Fermi names the new particle neutrino and introduces four-fermion interaction

1956 Reines and Cowan discover the neutrino

1962 At least two neutrinos: $\nu_e \neq \nu_\mu$

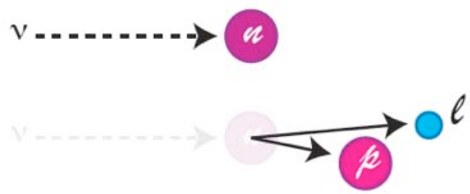
1973 Discovery of neutral currents at CERN

1983 Discovery of the W and Z

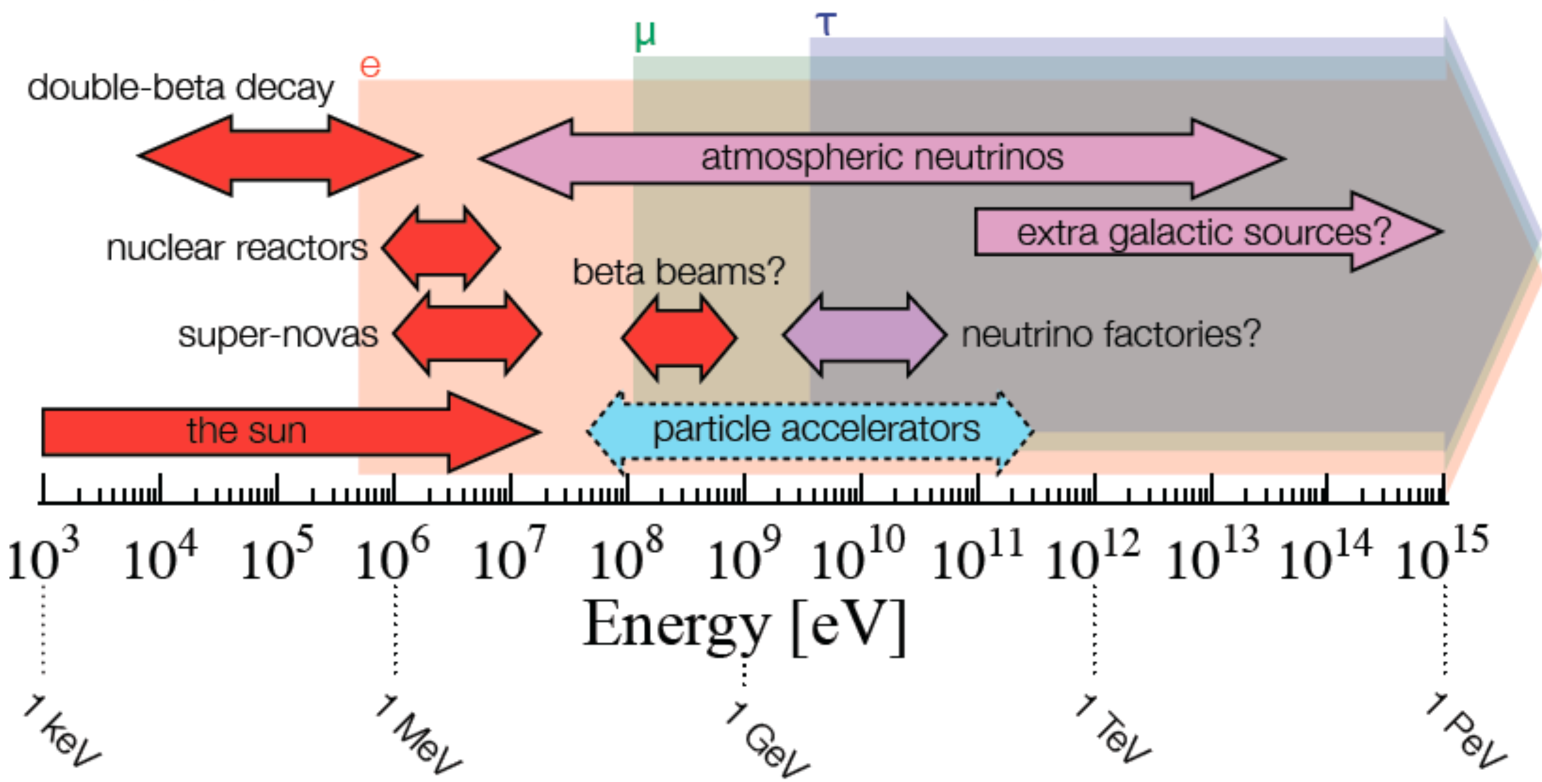
1989 Measurement of Z width at CERN $\rightarrow N_\nu=3$

2002 tau neutrino discovered.

Production Thresholds and ν Source energies



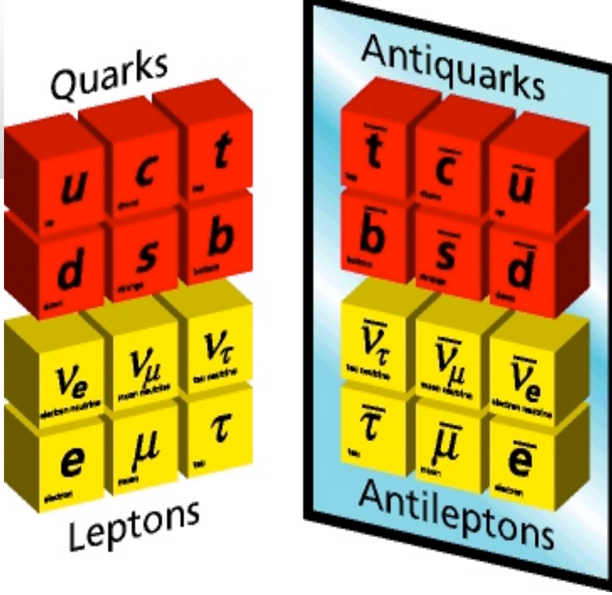
$$l = e \quad m_e = 0.511\ \mathrm{MeV} \quad P_{\mathrm{thresh}} = 0.511\ \mathrm{MeV}$$
$$l = \mu \quad m_\mu = 106\ \mathrm{MeV} \quad P_{\mathrm{thresh}} = 112\ \mathrm{MeV}$$
$$l = \tau \quad m_\tau = 1.78\ \mathrm{GeV} \quad P_{\mathrm{thresh}} = 3.47\ \mathrm{GeV}$$



Neutrinos Properties

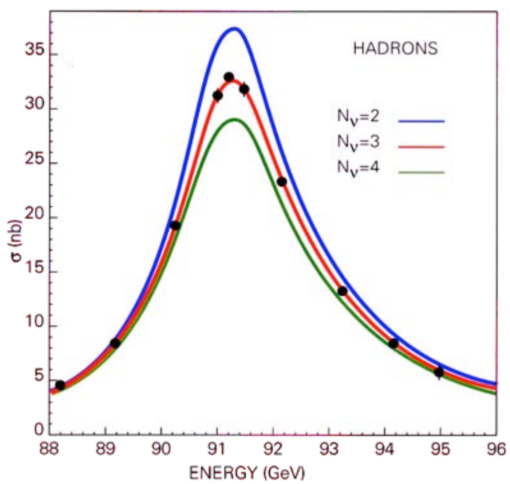
Neutrinos in the Standard Model

- point-like
- no charge
- 3ν flavors
- massless ν (*ad hoc* assumption in Standard Model)
- upper limits on m_ν from kinematic studies.
- weak and gravitational interactions

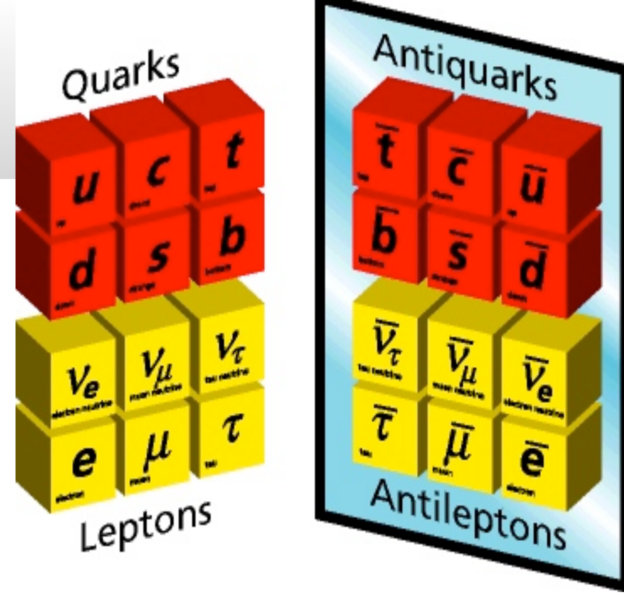


Discovery of ν_μ and ν_τ
Accelerator studies of ν

neutrinos as a clean probe



Neutrinos Properties



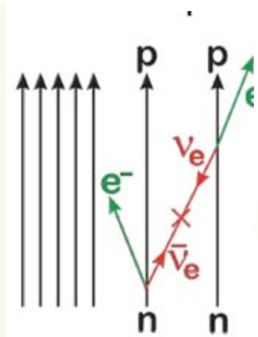
Neutrinos in the Standard Model

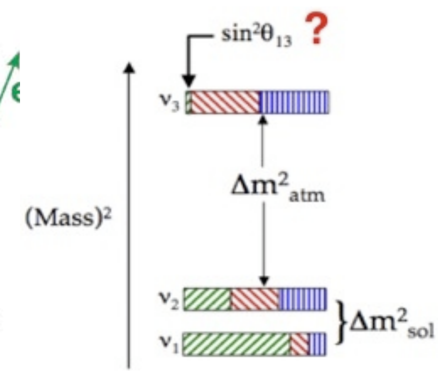
- pointlike
- no charge
- 3ν flavors
- massless ν (*ad hoc* assumption in Standard Model)
- upper limits on m_ν from kinematic studies.
- weak and gravitational interactions

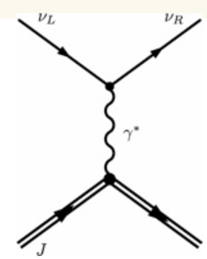
probing neutrinos = probing new physics beyond SM

Beyond the Standard Model

- number of mass states?
- Dirac vs Majorana mass?
- magnetic moment?
- mixing parameters
- CP violation?







$$\begin{pmatrix} \cos\theta_{13} & 0 & e^{-i\delta_{CP}}\sin\theta_{13} \\ 0 & 1 & 0 \\ -e^{i\delta_{CP}}\sin\theta_{13} & 0 & \cos\theta_{13} \end{pmatrix}$$

Neutrinos as a Probe – Probing Neutrinos

Neutrinos as a Probe

Understanding Matter and Interactions with Neutrinos

Reines-Cowan ν discovery
and the BNL 2ν experiment
fundamental ν properties

- hadronic weak currents
- observation of neutral currents
- cross sections

Bubble Chambers:
BNL, ANL, FNAL,
CERN, Serpukhov

counter experiments:
CDHS, CHARM
CCFR, NuTEV

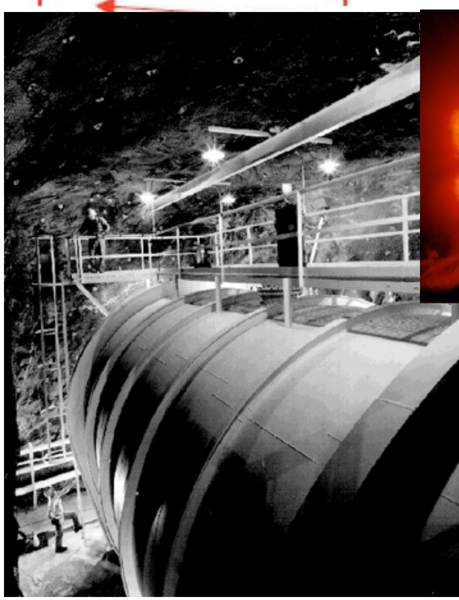
- structure functions (F_2, F_3)
- parton universality
- electroweak studies $\sin^2(\theta_W)$
- strange sea studies
- QCD measurements
- cross sections

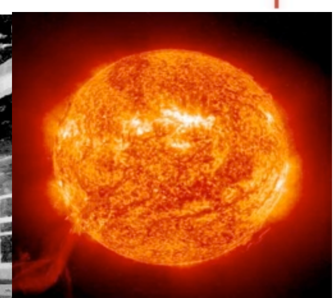
Neutrinos as probes to understand matter and interactions

Neutrinos as a Probe

Understanding Astrophysics

Reines-Cowan ν discovery
and the BNL 2ν experiment
fundamental ν properties



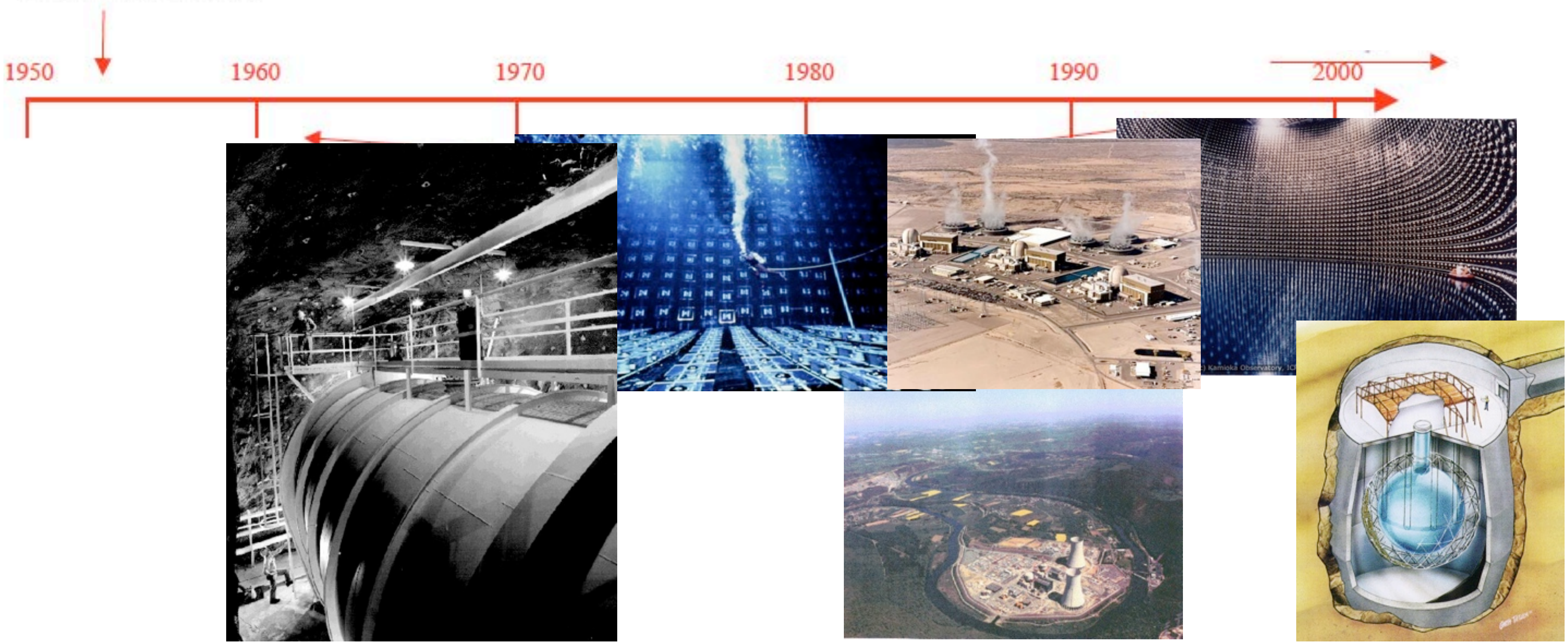


solar neutrinos

SN1987A
observation of astrophysical neutrinos

Neutrino Masses and Mixing, Non-Standard Effects

searches for neutrino oscillation with intense sources of ν_e, $\overline{\nu}_e$, ν_μ, ...

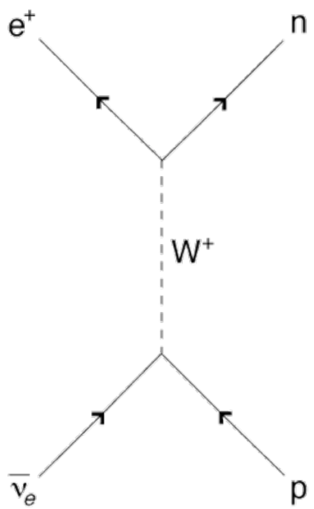


Experimental Challenges:

Cross-Sections
Detector Segmentation and Backgrounds

First Neutrino Cross-Section Calculation

1934 Bethe-Peirls: calculation of first cross-section for inverse beta



$\bar{\nu}_e + p \to n + e^+$ or $\nu_e + n \to p + e^-$ using Fermi theory

$\sigma \approx 5\times10^{-44}\ cm^2$ for $E(\bar{\nu}) = 2\ MeV$ Accurate to factor 2

Conversion from natural units: $\hbar c = 197.3\ MeV \cdot fm$

Cross-section: multiply by $(\hbar c)^2 = 0.3894\times10^{-27}\ GeV^2 \cdot cm^2$

Mean free path of antineutrino in water:

$$\lambda = \frac{1}{n\sigma} \approx 1.5\times10^{21}\ cm \approx 1600\quad light-years$$

$$n = \frac{\text{num. free protons}}{\text{volume}} \approx 2\frac{N_A}{A}\rho$$

In water: $n = \dfrac{2\times6\times10^{23}}{18} = 6.7\times10^{22}\ cm^{-3}$

- Probability of interaction:

$$P = 1 - \exp\left(-\frac{L}{\lambda}\right) \approx \frac{L}{\lambda} = 6.7\times10^{-20}\ (m\ water)^{-1}$$

Need very intense source of antineutrinos to detect inverse beta reaction.

Neutrino Cross Section is Small

Weak interactions are weak because of the massive W and Z boson exchange

$$\sigma^{weak} \propto G_F^2 \propto (1/M_{W\ or\ Z})^4$$

$M_W \sim 80$ GeV

$M_Z \sim 91$ GeV

$$G_F = \frac{\sqrt{2}}{8}\left(\frac{g_W}{M_W}\right)^2 = 1.166\times 10^{-5}/GeV^2 \quad (g_W \approx 0.7)$$

For 100 GeV neutrinos: $\sigma(\nu e) \sim 10^{-40}$

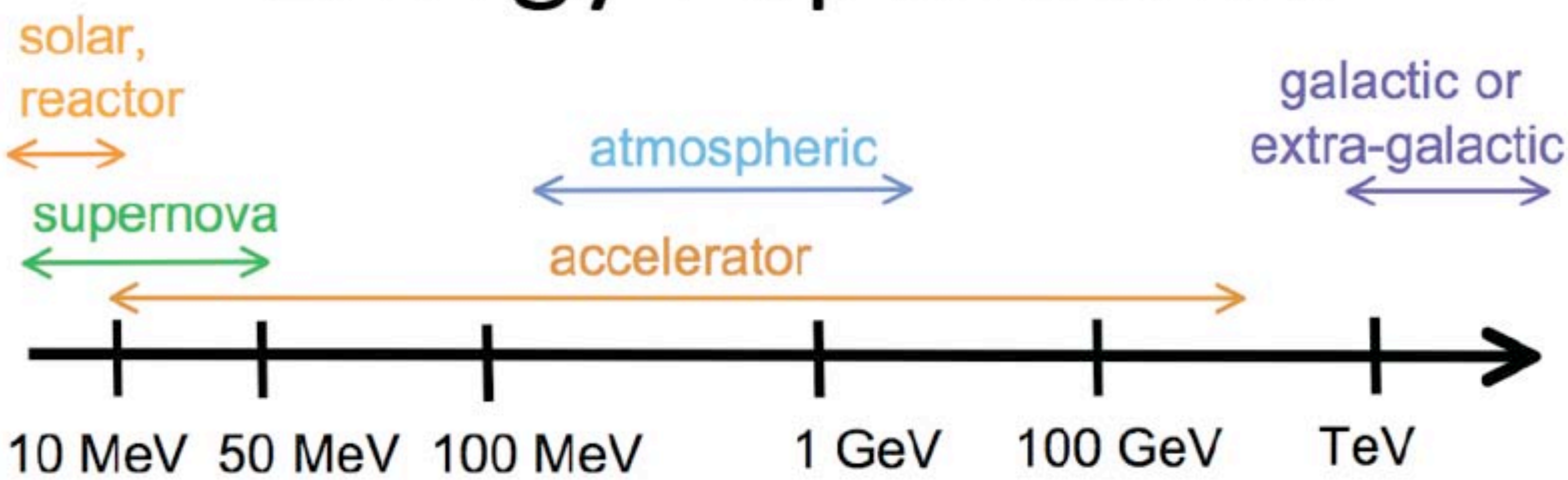
$\sigma(\nu p) \sim 10^{-36}$ cm^2

$\sigma(pp) \sim 10^{-26}$ cm^2

Mean free path length in steel $\sim 3\times 10^9$ m

$\rightarrow$ Need big detectors and lots of ν's

Energy dependence



- **target description** is different depending on the ν energy

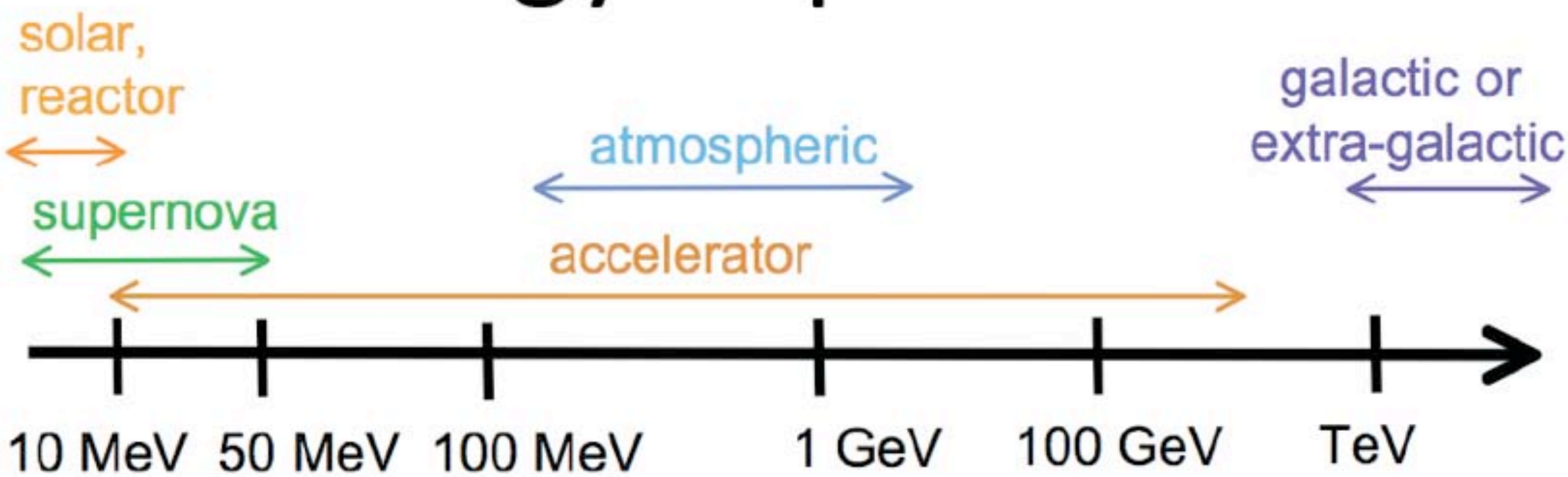
ν-nucleon ··········> **ν-quark**

elastic scattering
(nucleon form factors)

can also create **resonances**
(another type of inelastic interaction)

inelastic scattering
(parton density functions)

Energy dependence

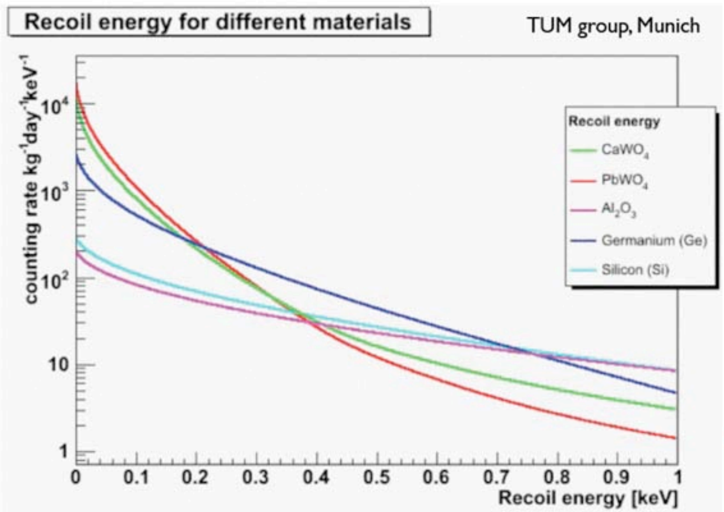


- also, treatment of **nuclear effects** is energy dependent …

shell model, RPA, EFT ⇢ impulse approximation (Fermi Gas, spectral functions, etc.) ⇢ quark parton model

Energy Dependence of Neutrino Interactions

Searching for new effects (Coherent ν-A scattering)

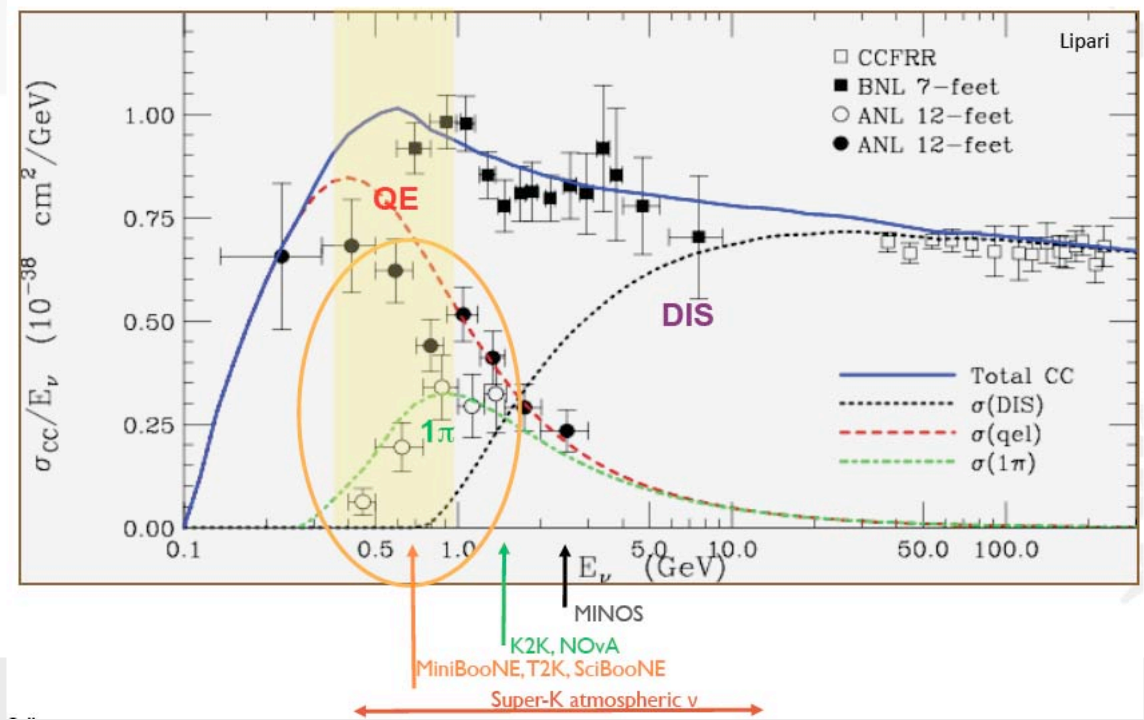


Coherent ν-A elastic $\sigma \sim 10^{-39}$ cm^2

Max Energy of recoil nucleus ~ $2E_\nu^2$ /M

SM process

Understanding neutrino oscillations and cross-sections



Detector Segmentation

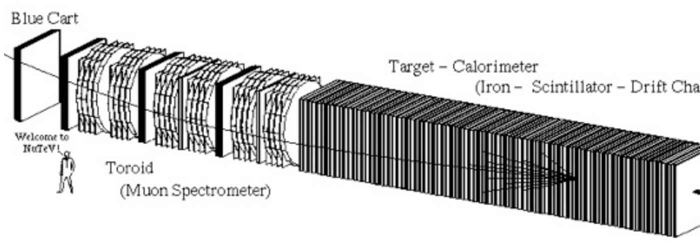
Detectors are often homogeneous due to large size requirement

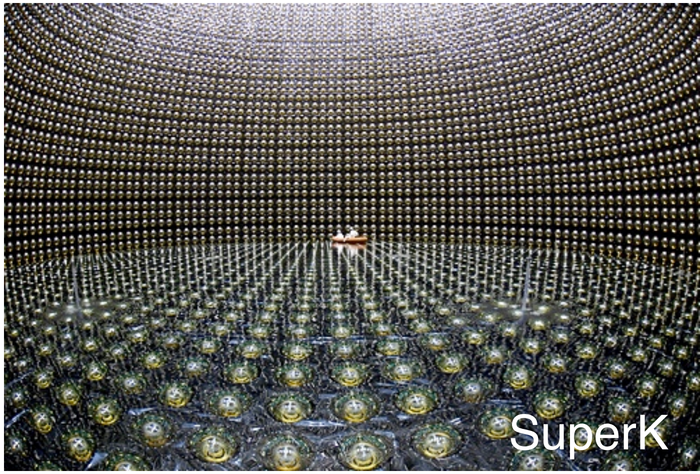
Geometries

- Segmented (sampling): Instrumented in small volumes. Target may not be the active detector element.
- Unsegmented (fully active): Volume instrumented as a whole.Target is active detector element

Background Suppression

- Passive shielding from cosmic rays at ~200Hz/m_2 on surface
  - segmented may be OK on surface
  - unsegmented go underground
- Time correlation with neutrino source (e.g. beam)
- Active background discrimination





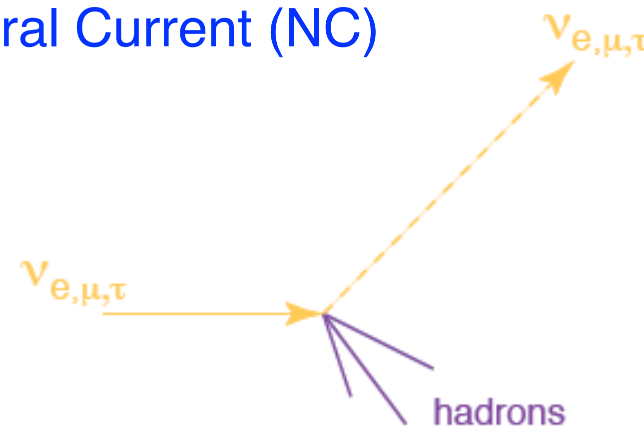
Detectors in Neutrino Physics:

Detection Channels
Particle Signatures

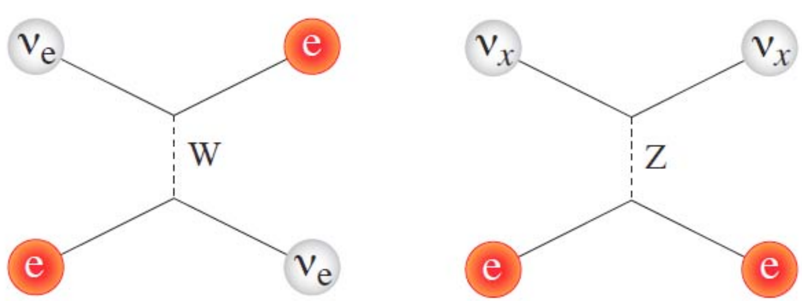
Neutrino Detection and Particle Signatures

Detect particles when neutrinos interact with nuclei or electrons bound to nuclei

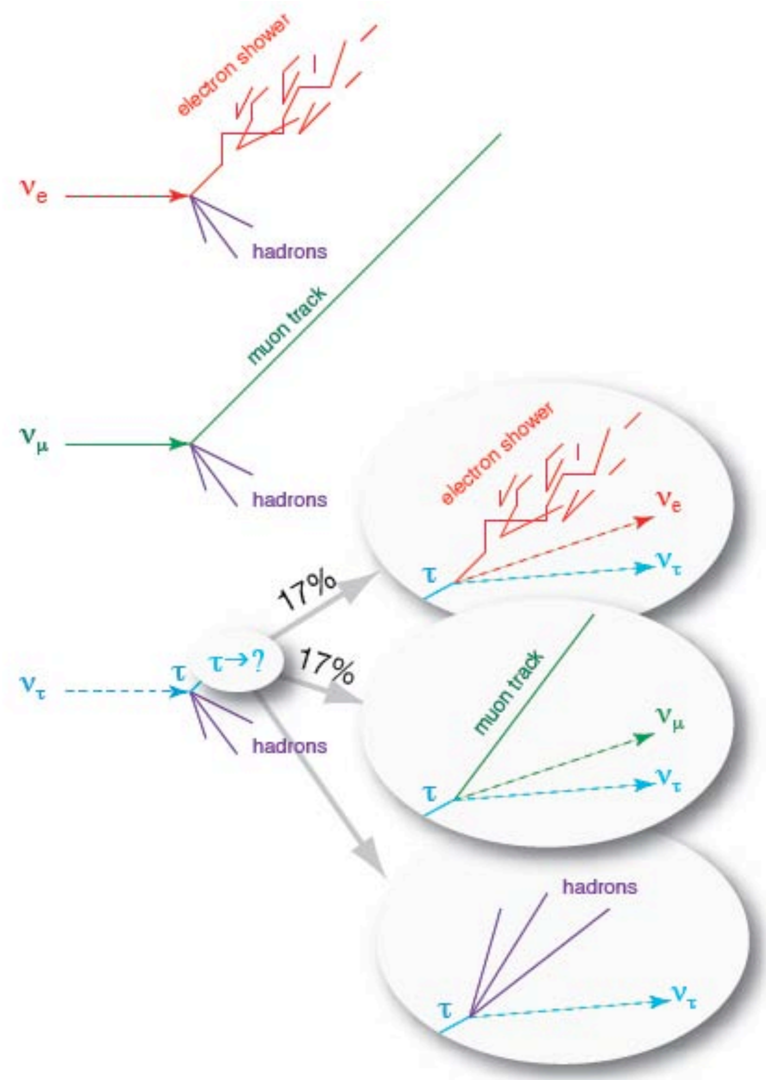
Neutral Current (NC)



Elastic Scattering (ES)

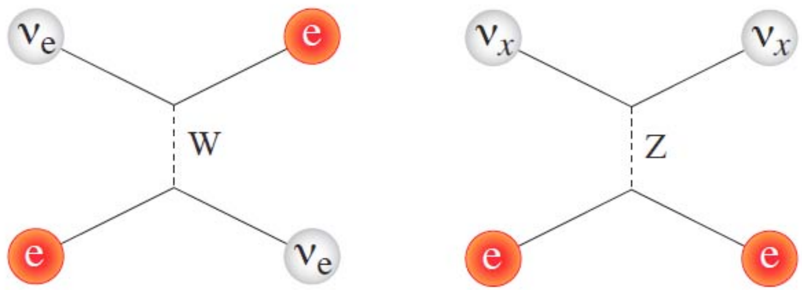


Charged Current (CC)



Neutrino Detection and Particle Signatures

Elastic Scattering (ES)

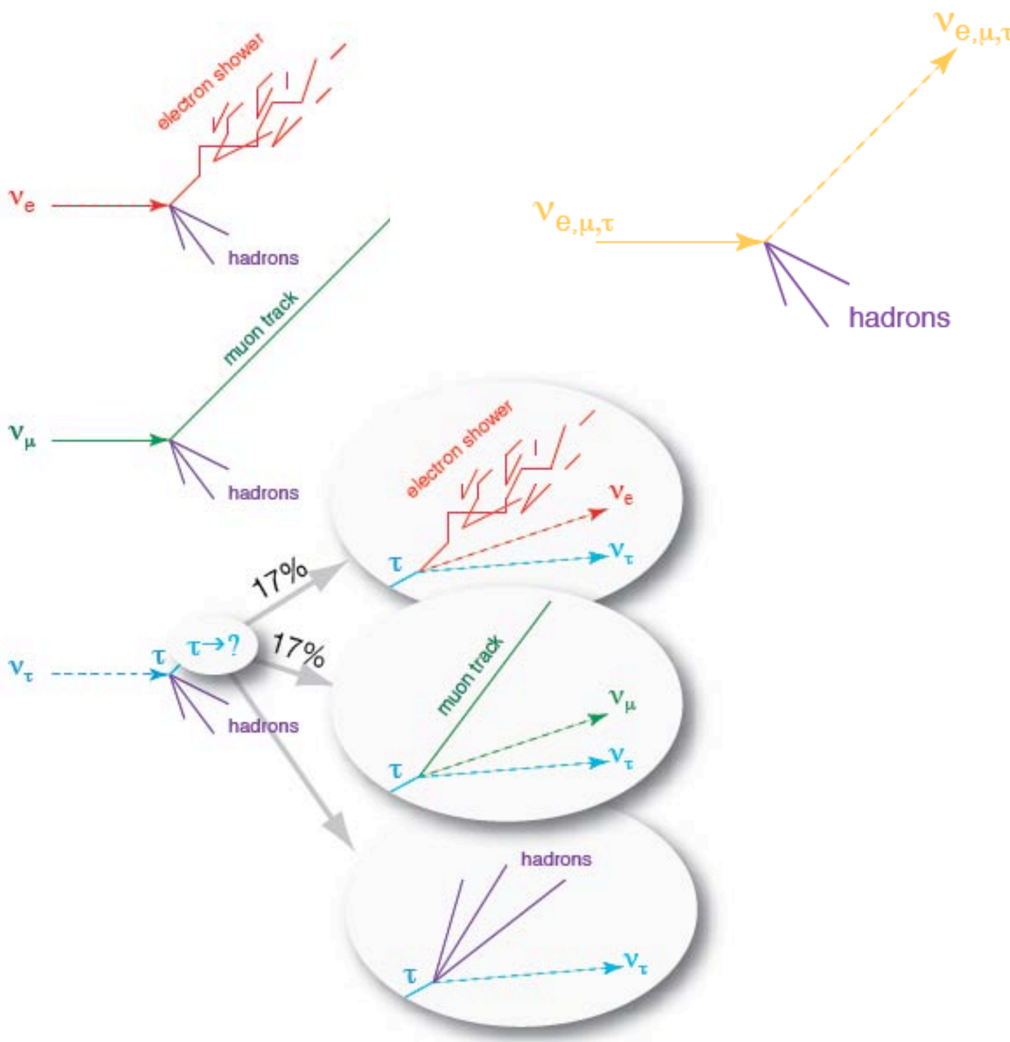


Cross-sections for nucleons turn off below 200 MeV. At low energies we can use target containing free nucleons, or neutrino-electron elastic scattering.

Elastic Scattering
- electron sent primarily in forward direction
- energy of electron ~ uniformly distributed between 0 and E_ν
- $\sigma_{CC}/\sigma_{NC} \sim 1/6$

Neutrino Detection and Particle Signatures

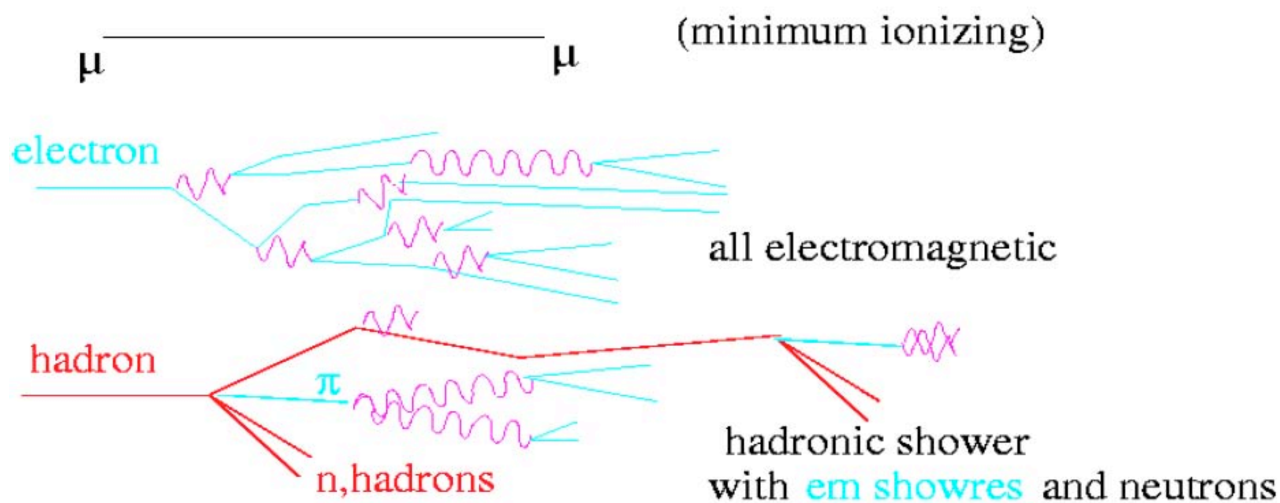
Charged Current (NC) and Neutral Current (NC)



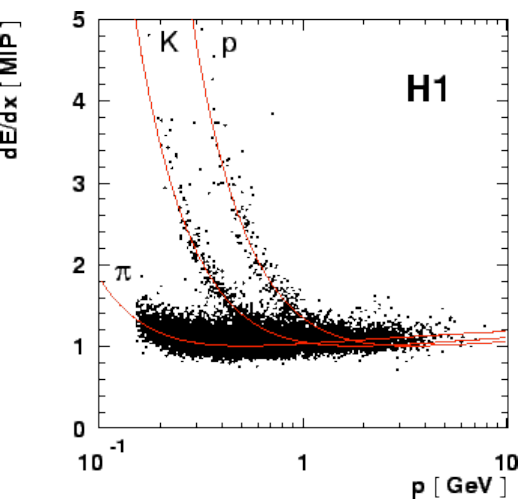
Charged Current
- outgoing lepton tags incoming ν flavor
- nearly all ν energy is deposited in the detector
- rates affected by (active) neutrino oscillations

Neutral Current
- only hadrons present, no information on incident neutrino flavor
- NC rates not affected by oscillation
- in many cases NC events are background to the CC processes

Neutrino Detection and Particle Signatures

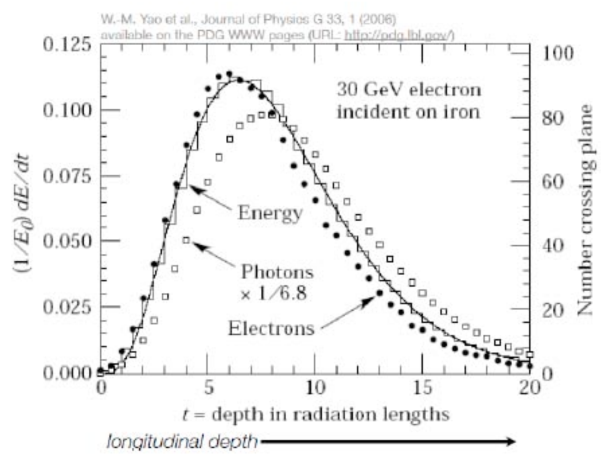


ionization loss



dE/dx from Bethe Bloch

electromagnetic showers



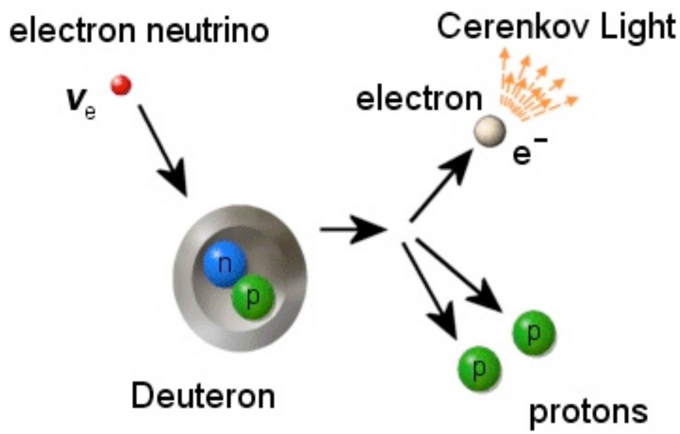
e- will create Bremsstrahlung, e^+e^-

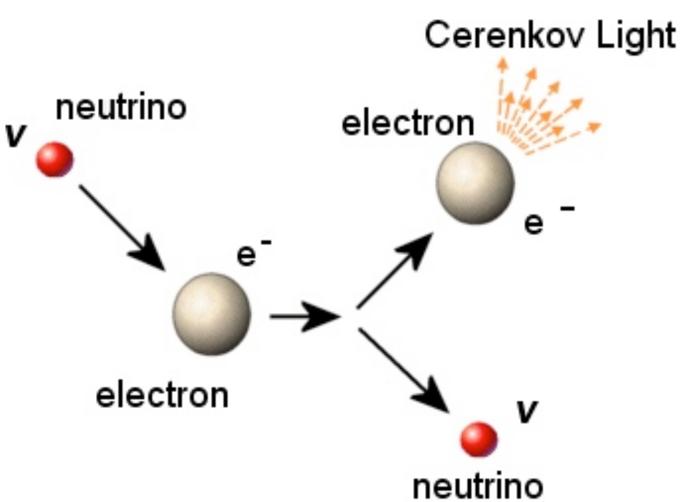
hadronic showers

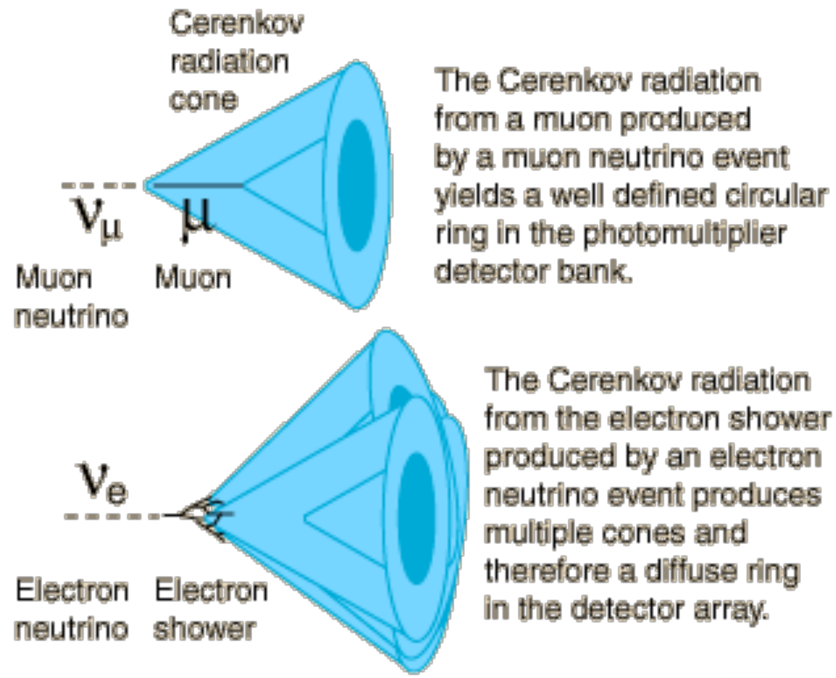
- similar to EM shower but different interactions
- π^0 are produced which decay to photons, which the proceed electromagnetically
- neutrons may be made in shower which show no visible energy

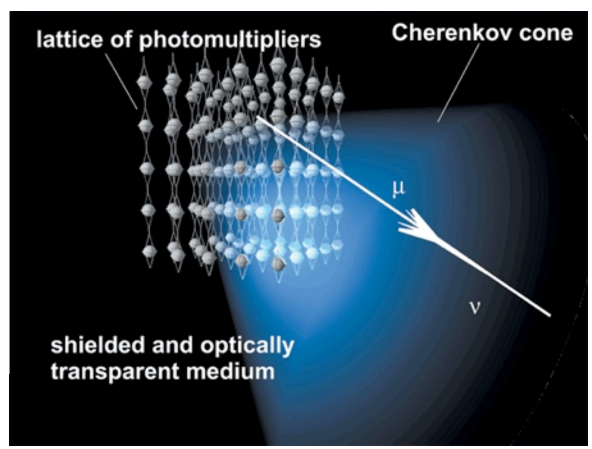
Neutrino Detection and Particle Signatures

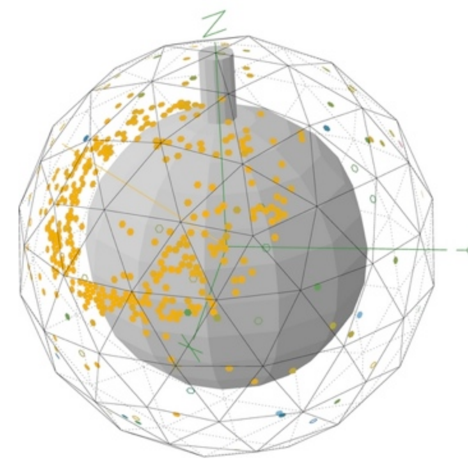
Cherenkov Light





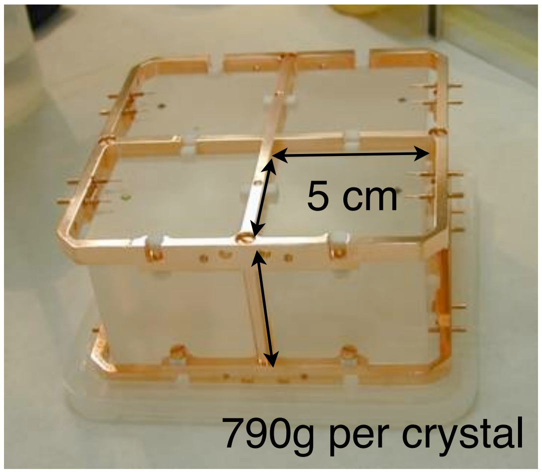


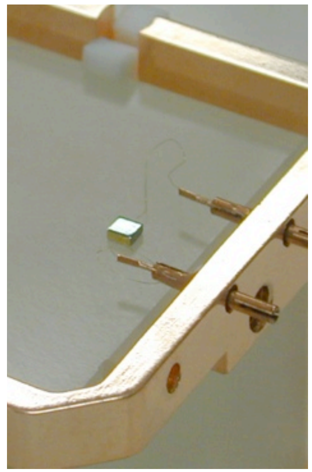


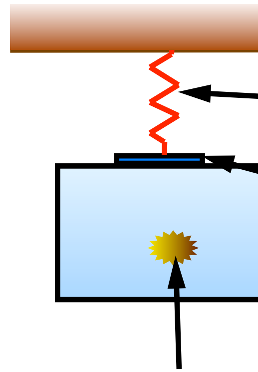


Neutrino Detection and Particle Signatures

Bolometric Signal







Heat sink:
Cu structure (8-10 mK)
Thermal coupling:
Teflon (G = 4 pW/mK)
Thermometer:
NTD Ge-thermistor
(dR/dT ≅ 100 kΩ/μK)
Absorber:
TeO_2 crystal

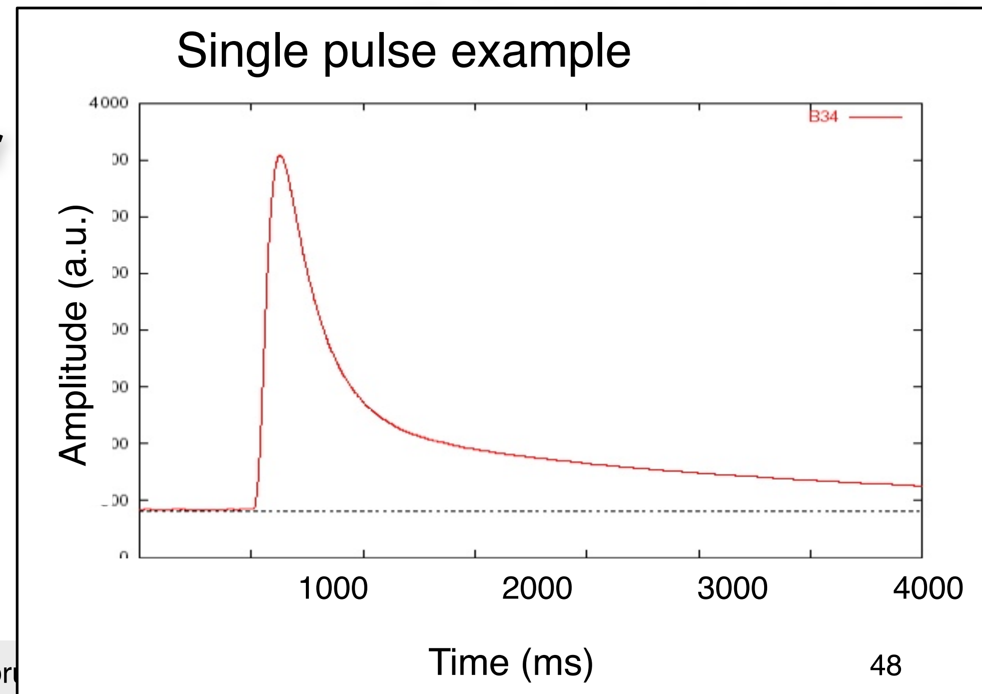
deposited energy

TeO_2 Bolometer: Source = Detector

For E = 1 MeV: $\Delta T = E/C \cong 0.1$ mK
Signal size: 1 mV

voltage signal ∝ energy deposited

Time constant: $\tau = C/G = 0.5$ s
Energy resolution: ~ 5-10 keV at 2.5 MeV



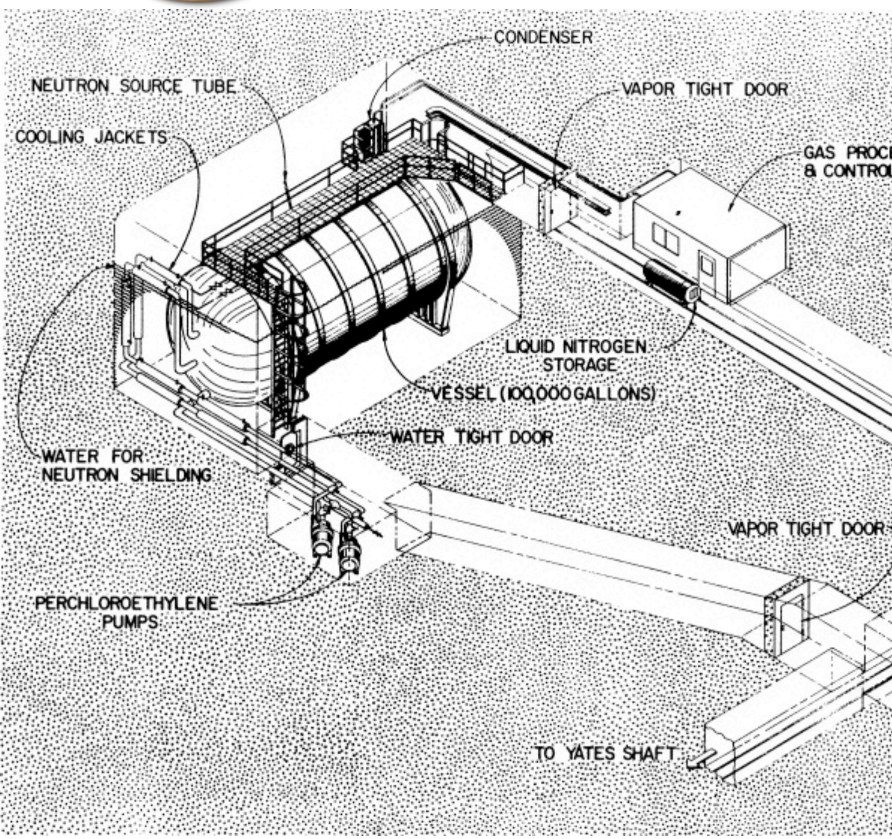
Neutrino Detection and Physics Goals

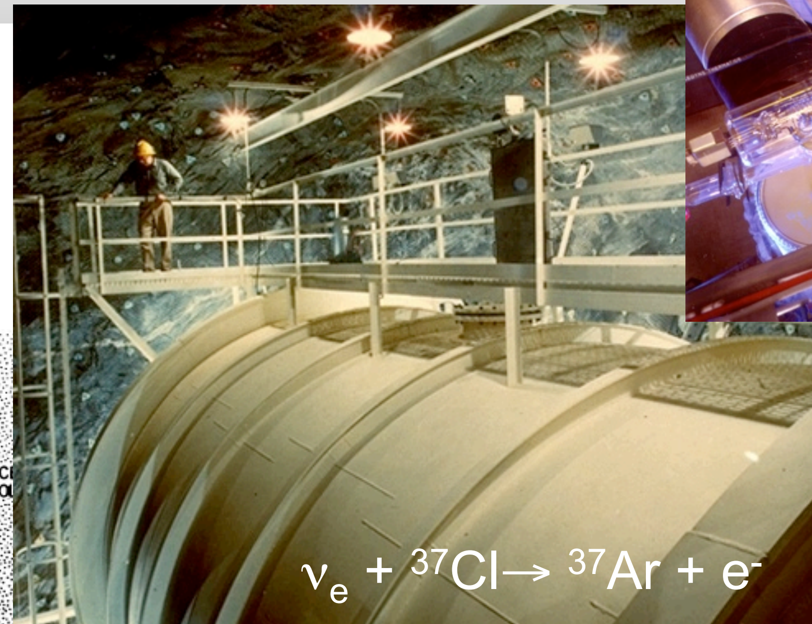
- Neutrino Oscillation Measurement
  - identify flavor of neutrino
    - unique flavor channels (e.g. SNO)
    - lepton identification (e.g. accelerator)
  - measure energy

- Neutrino Interaction Measurement
  - measure different interaction channels
  - measure total energy of events (all final states)
  - identify neutrino vs antineutrinos
  - initial and final nucleus (for nuclear effects)

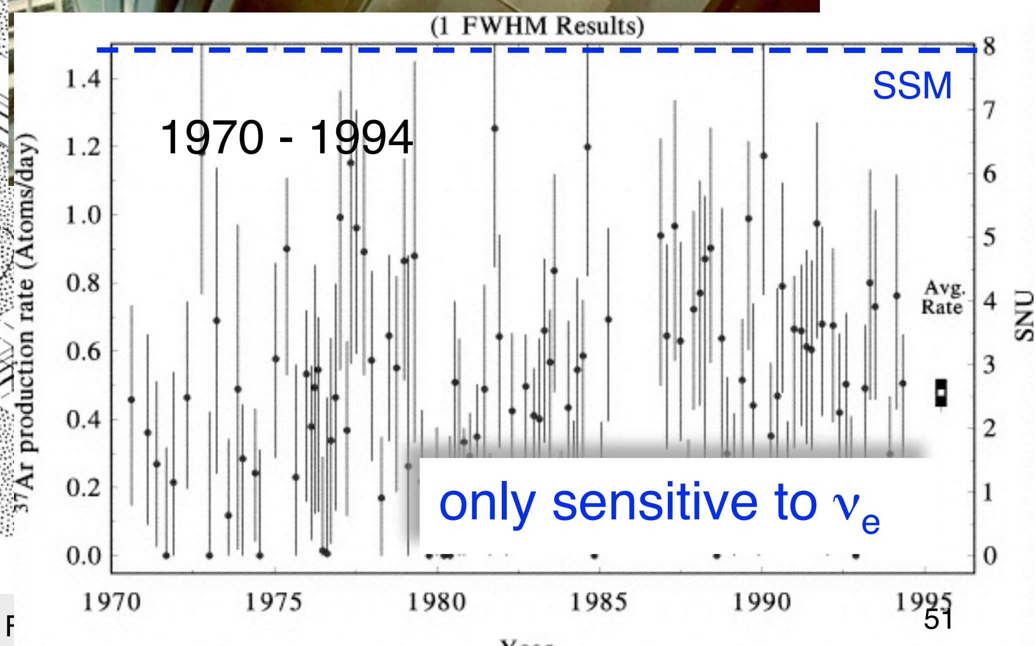
Detectors in Neutrino Physics: Present and Future

Cl-Ar Solar Neutrino Experiment at Homestake



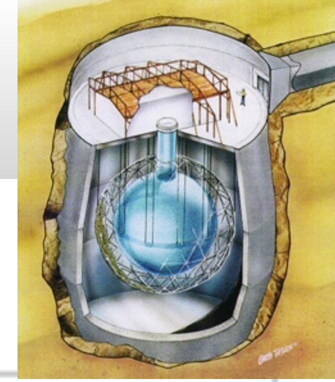


$\nu_e + {}^{37}Cl \rightarrow {}^{37}Ar + e^-$



only sensitive to ν_e

Neutrino Detection in SNO



Neutrino Interactions on Deuterium and their Flavor Sensitivity

Charged-Current (CC)

$\nu_e + d \rightarrow e^- + p + p$

$E_{thresh} = 1.4$ MeV

Measurement of energy spectrum

Neutral-Current (NC)

$\nu_x + d \rightarrow \nu_x + n + p$

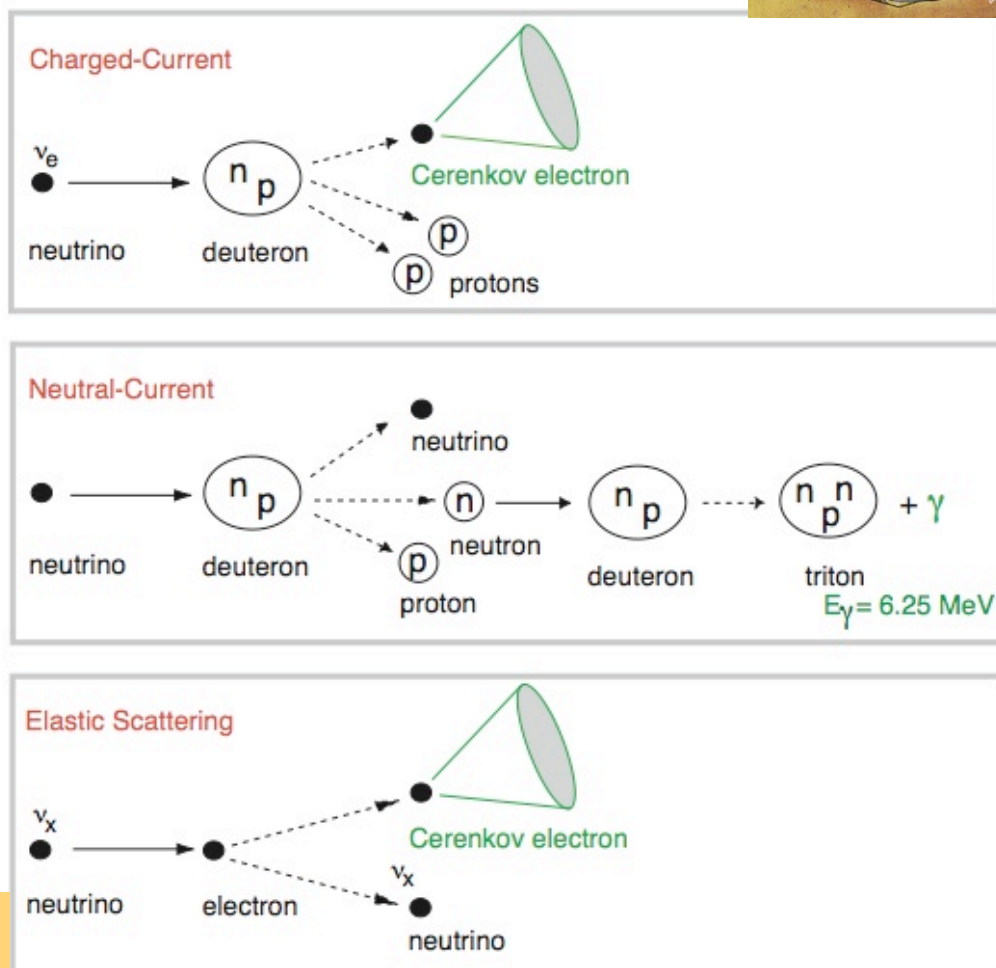
$E_{thresh} = 2.2$ MeV

Measures total ^8B flux from Sun

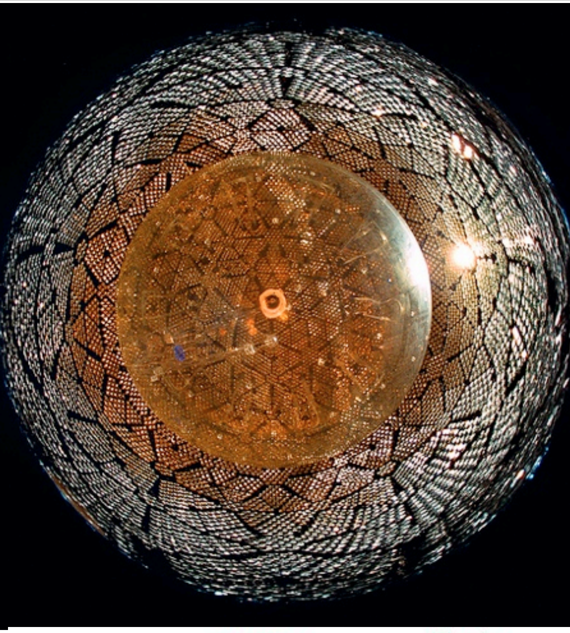
Elastic Scattering (ES)

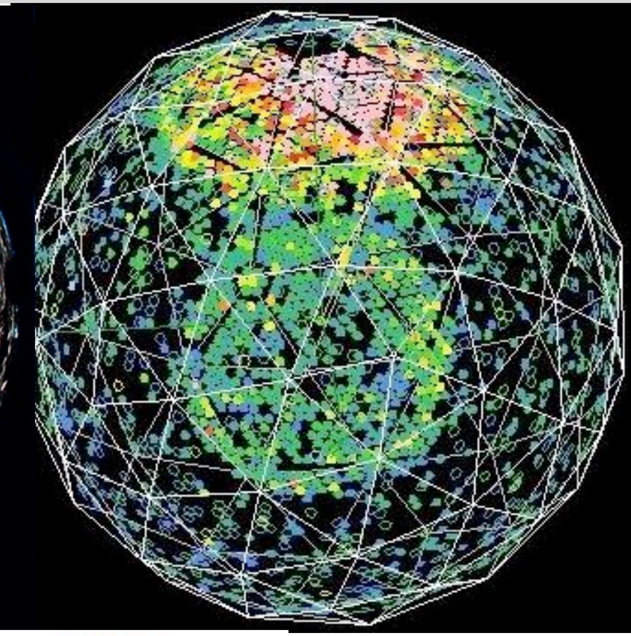
$\nu_x + e^- \rightarrow \nu_x + e^-$

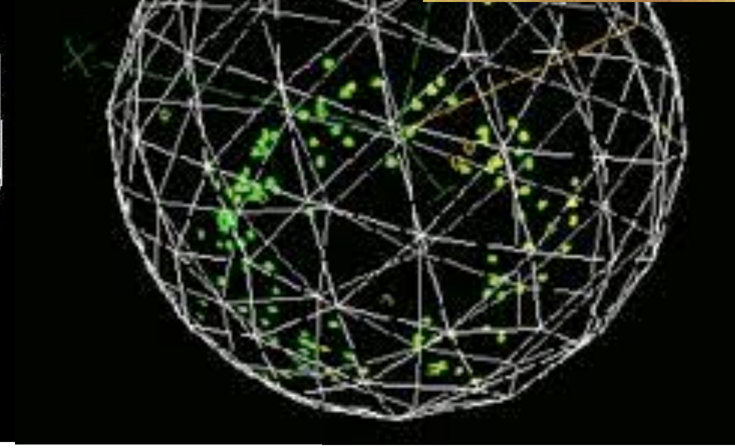
sensitivity to all neutrino flavors

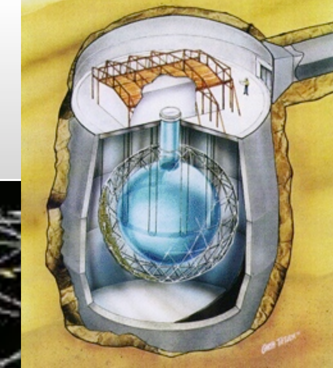


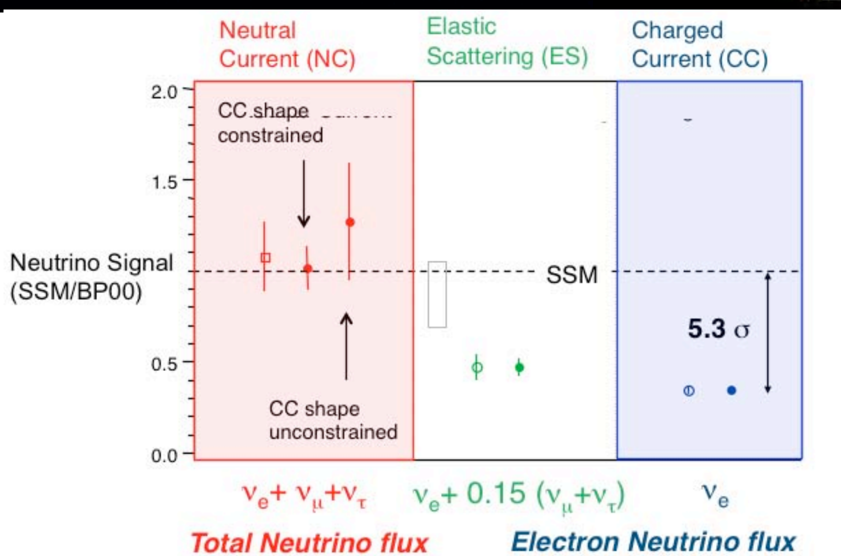
Neutrino Detection in SNO

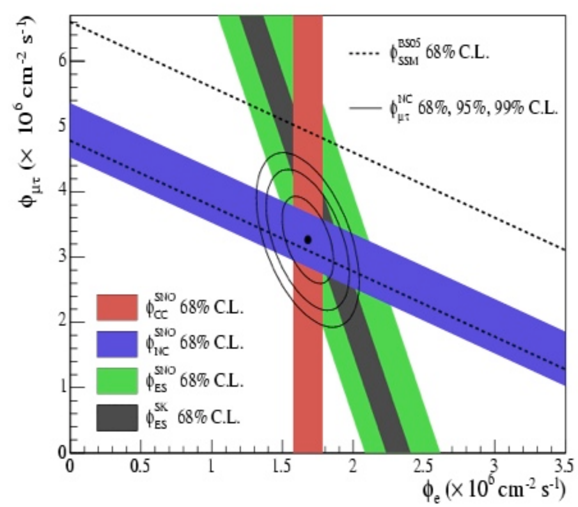






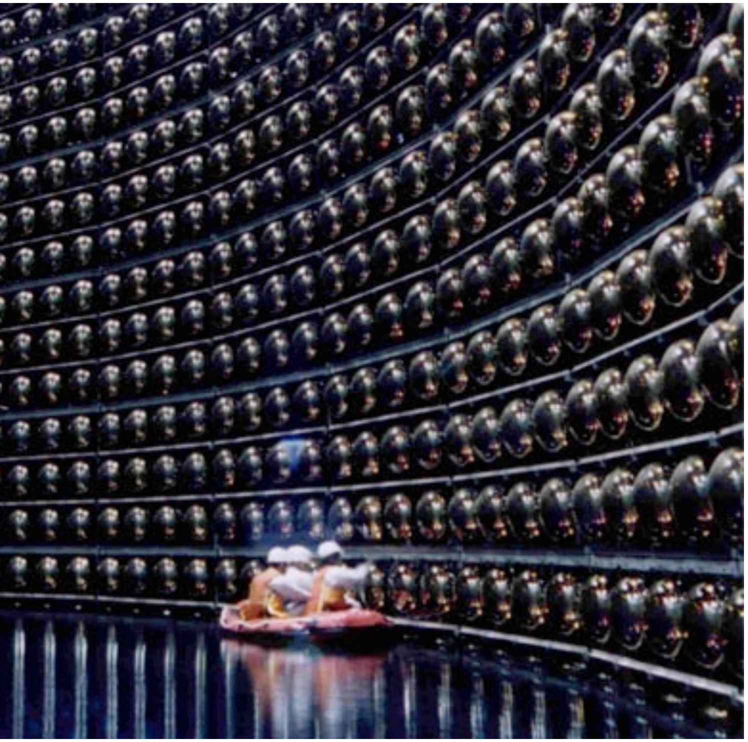


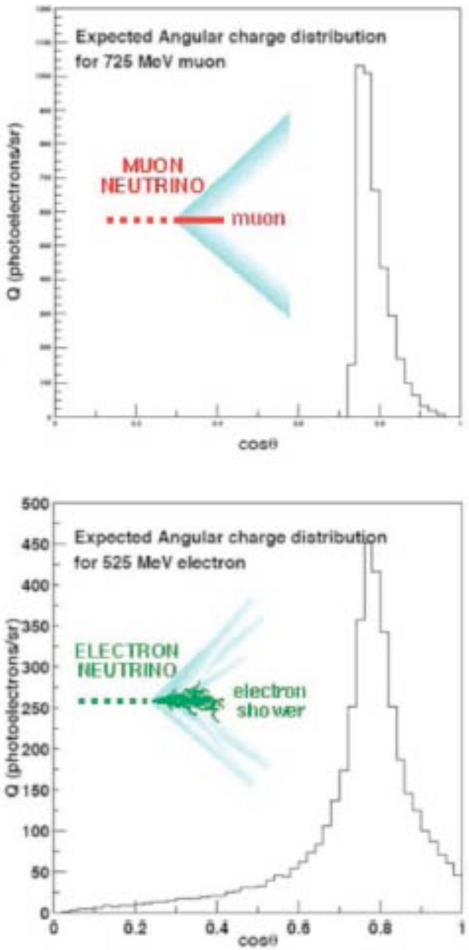


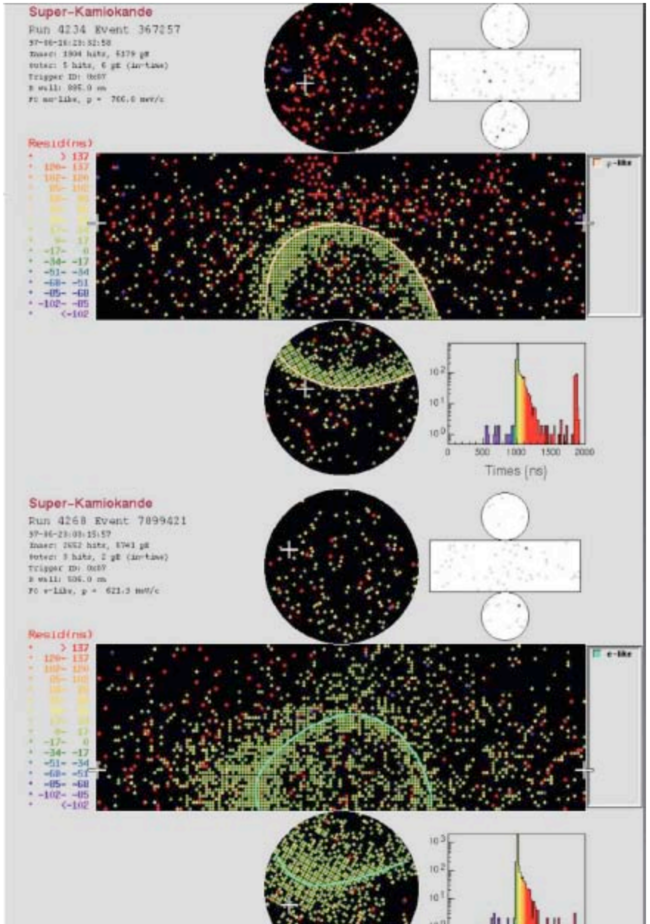


Super-Kamiokande

atmospheric neutrinos



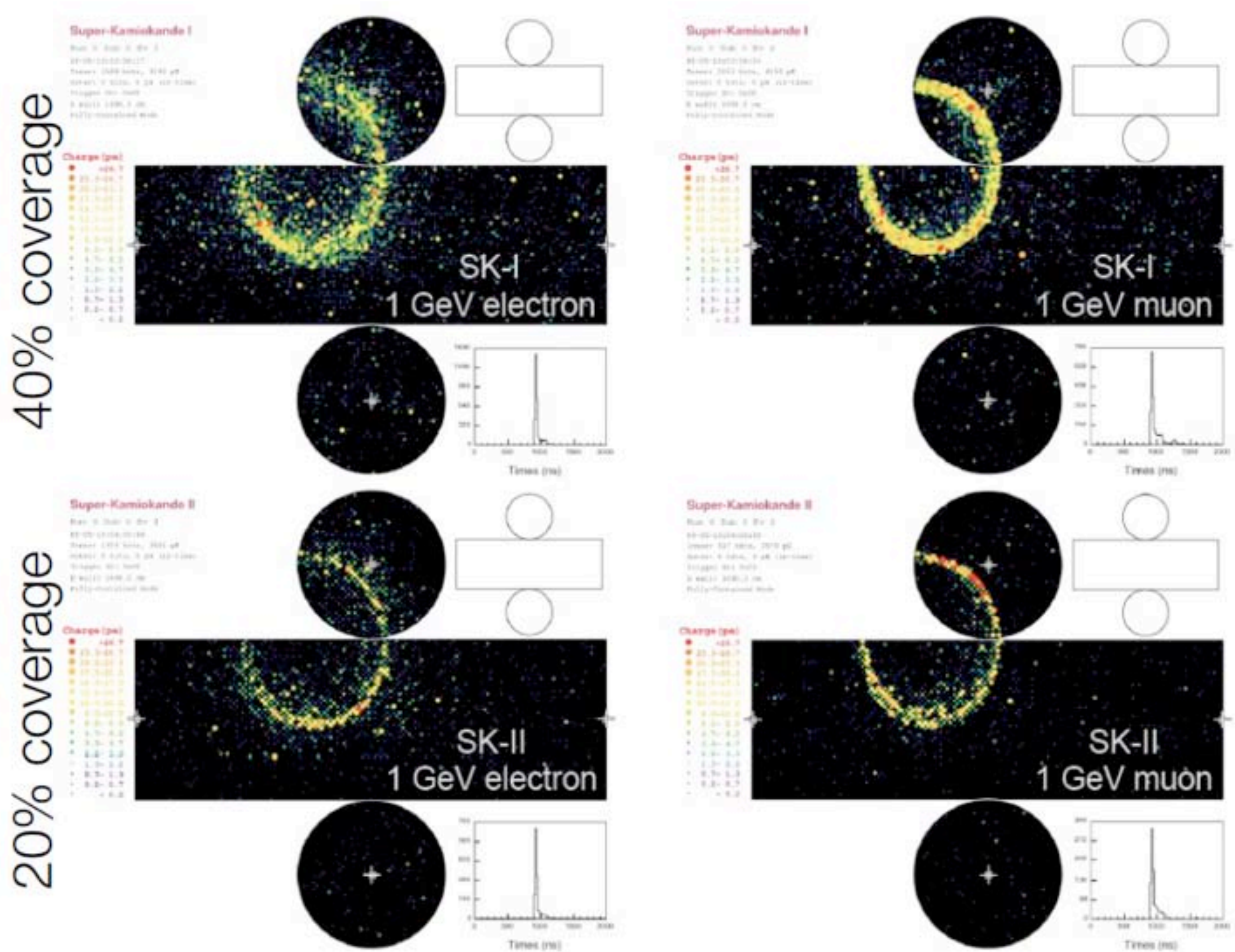




Figures from
http://hep.bu.edu/~superk/atmnu/

Super-Kamiokande

atmospheric neutrinos

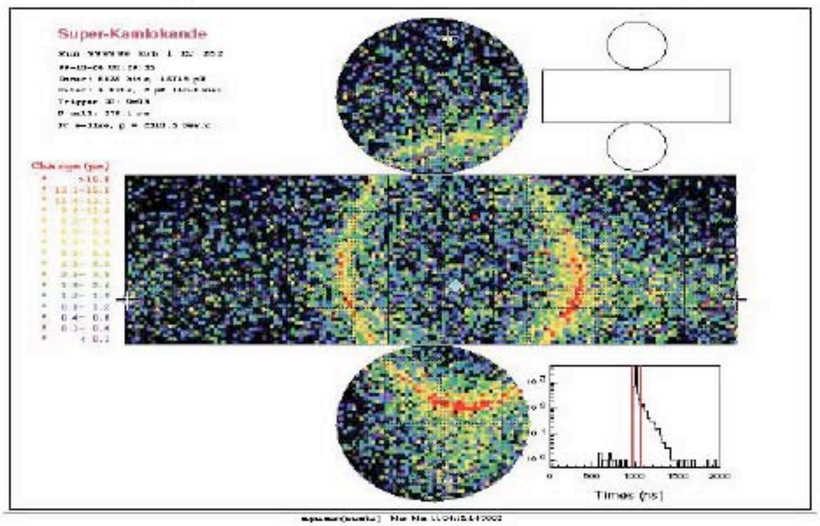


Super-Kamiokande

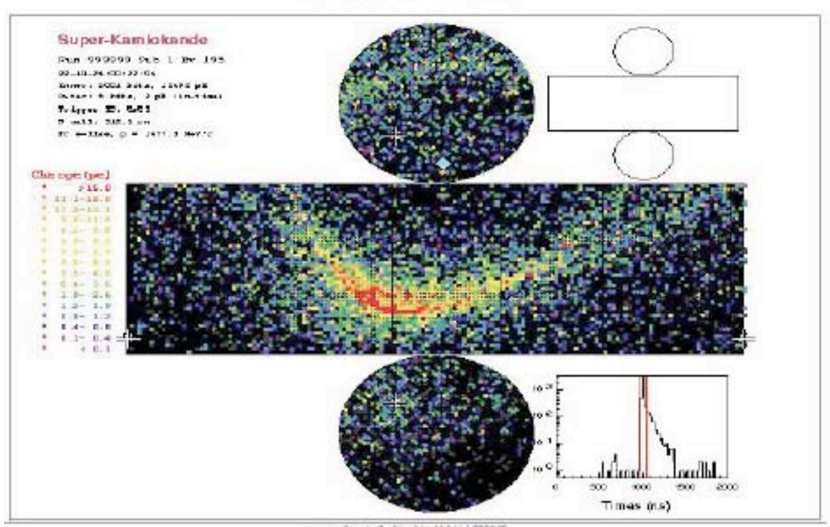
atmospheric neutrinos

2 GeV visible energy

one is signal, one is background

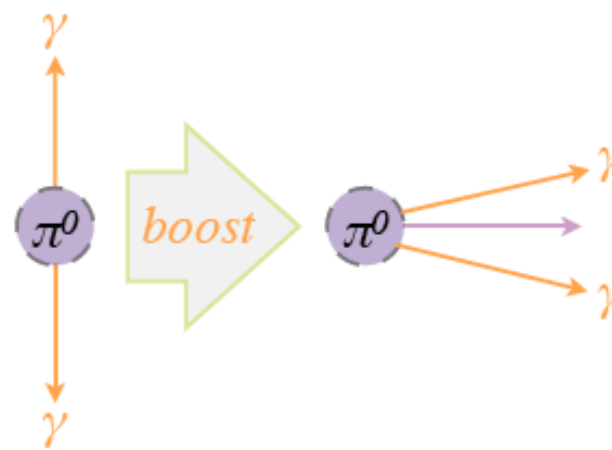


ν_e CC

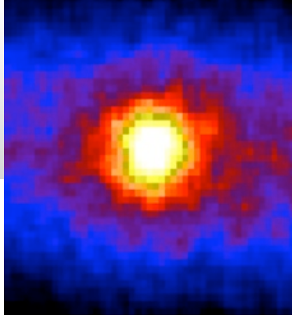


NC π^0

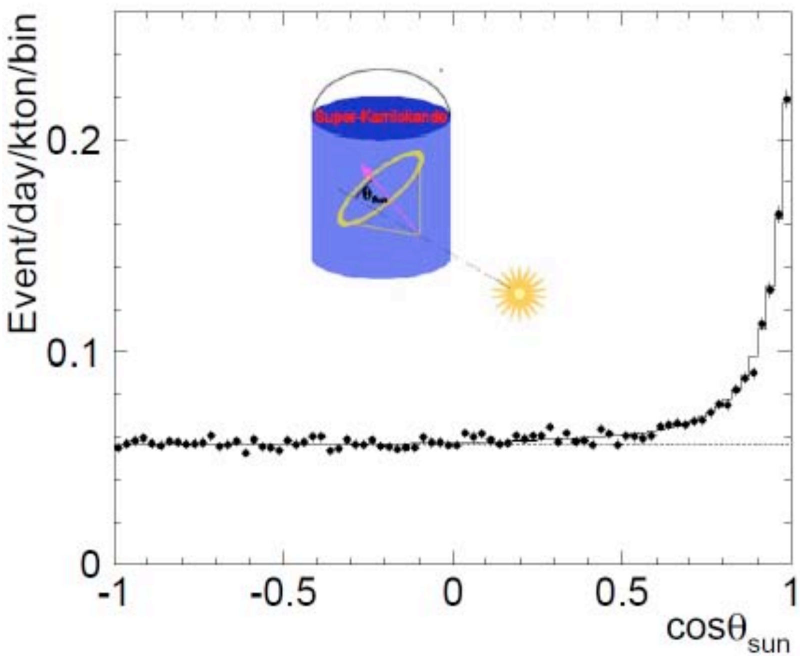
π^0 decay at high energy

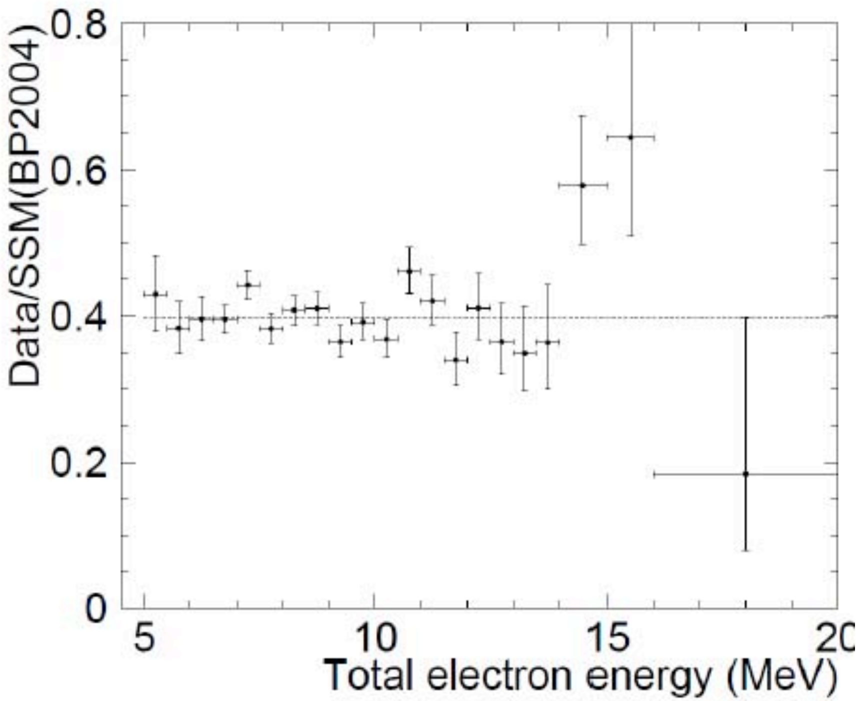


Super-Kamiokande

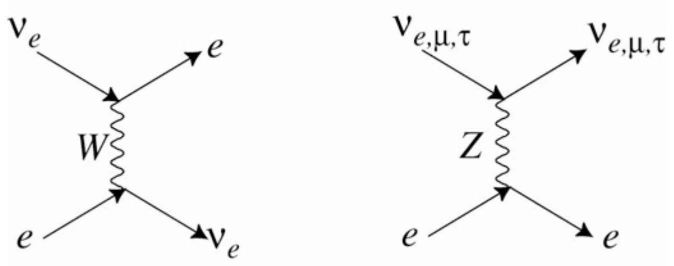


solar neutrinos



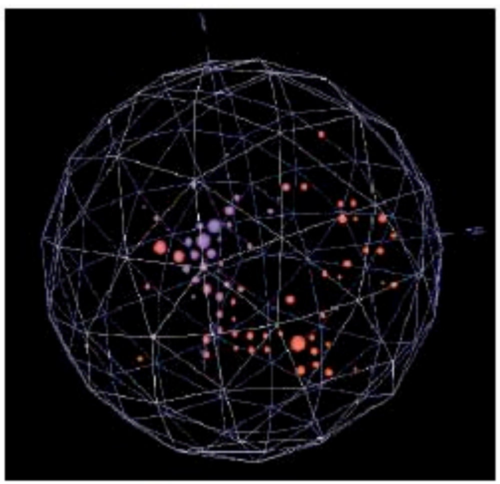


Through electron scattering

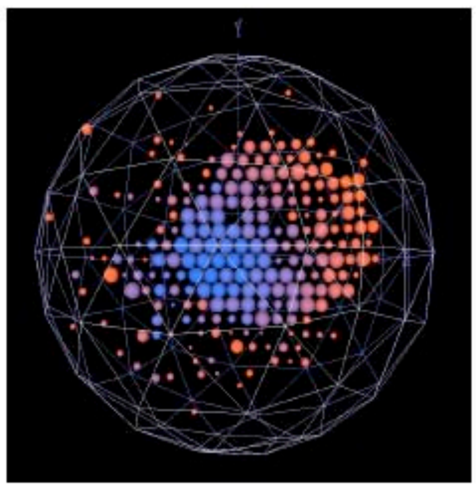


MiniBoone

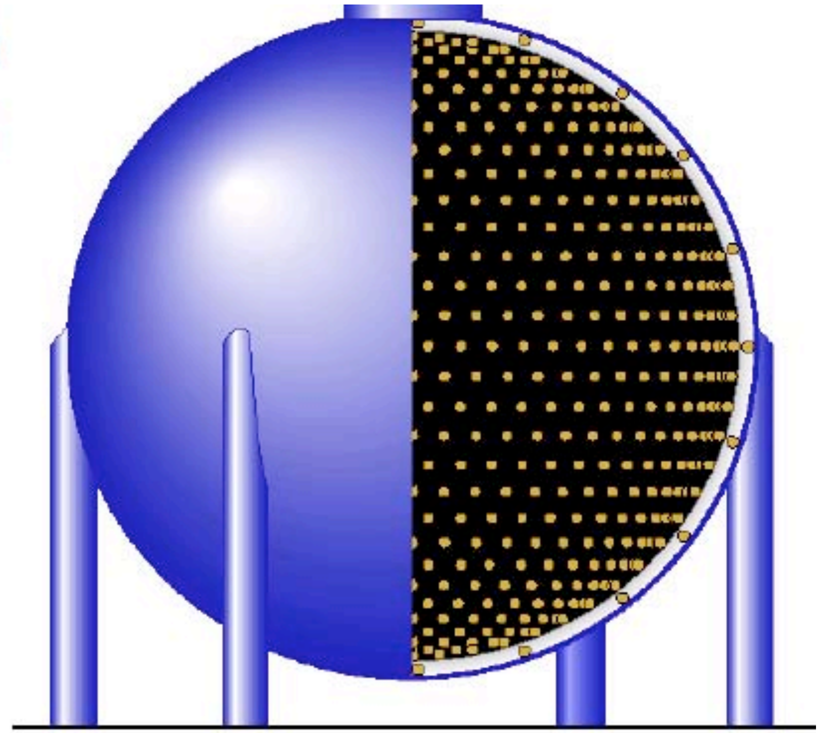
total volume: 800 tons (6 m radius)
fiducial volume: 445 tons (5m radius)
1280 PMTs in detector at 5.5 m radius
10% photocathode coverage
240 PMTs in veto



electron ring



μ ring



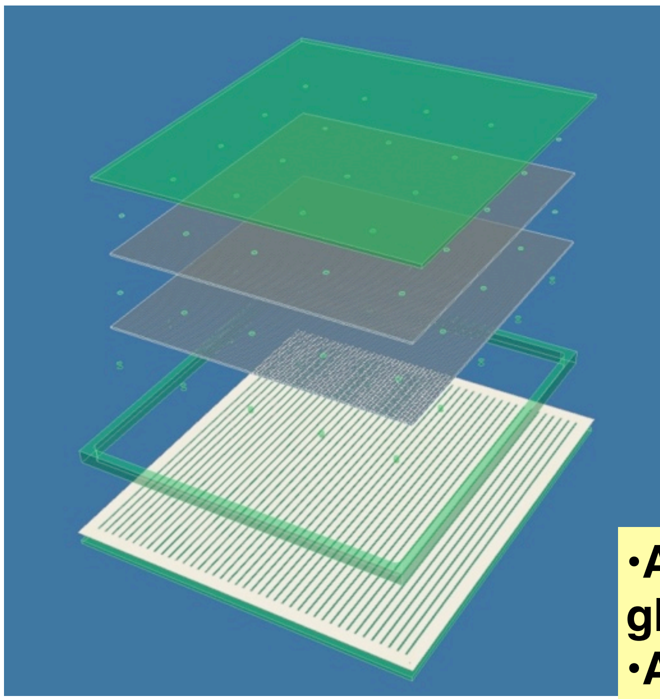
Events courtesy G. Zeller

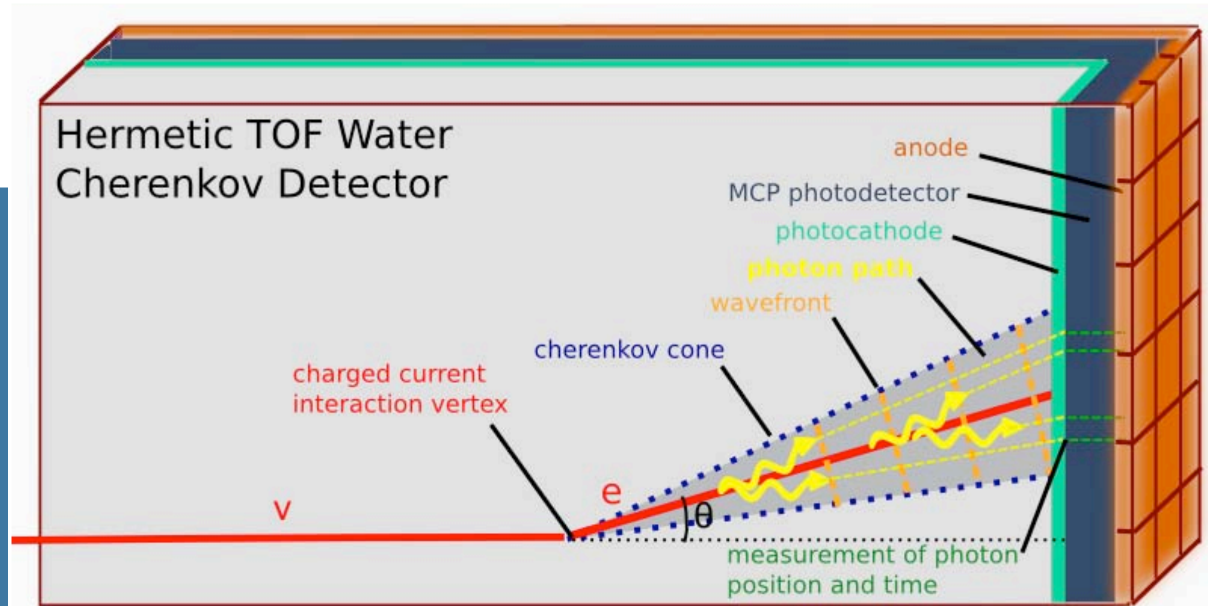
Cherenkov events in oil

A common issue:
photo detection for large water/scintillator/LAr detectors

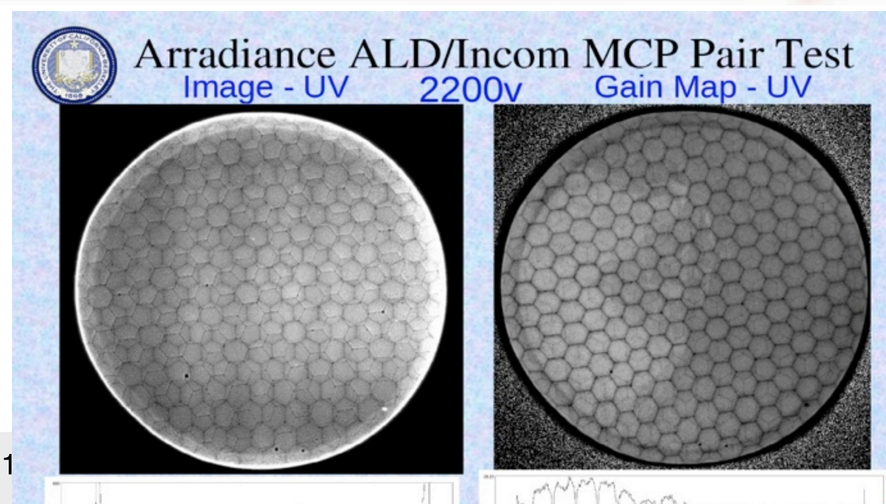
low cost, single PE, low background,…

- **Large area, low cost MCP**





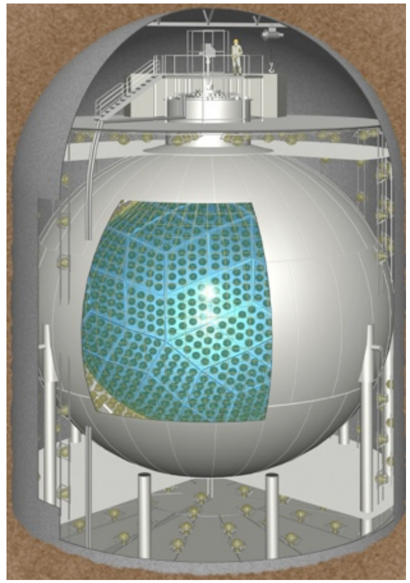
•All (cheap) glass
•Anode is silk-screened

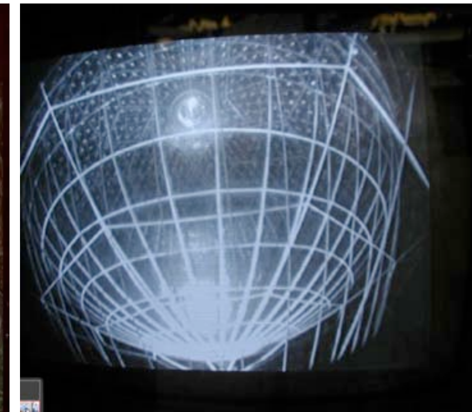


R&D project by Henry Frisch et al.

Reactor Neutrino Experiments

KamLAND



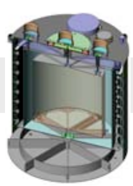


inverse beta decay

$\overline{\nu}_e + p \rightarrow e^+ + n$

Near-Far Concept

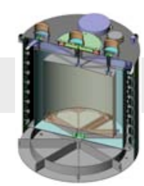
$\overline{\nu}_e$



near

$\overline{\nu}_{e,x}$

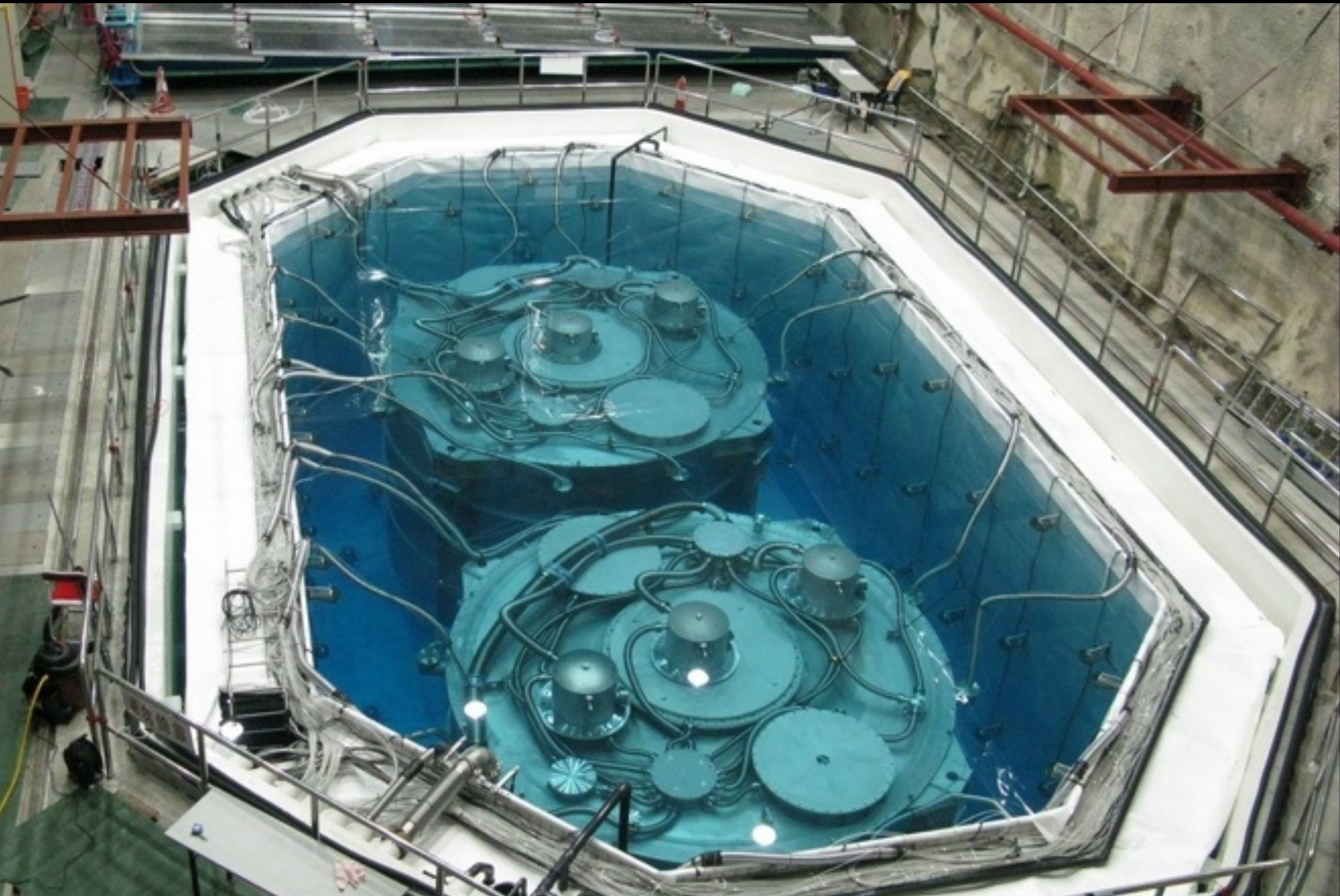
distance L ~ 1.5 km



far

$\overline{\nu}_{e,x}$

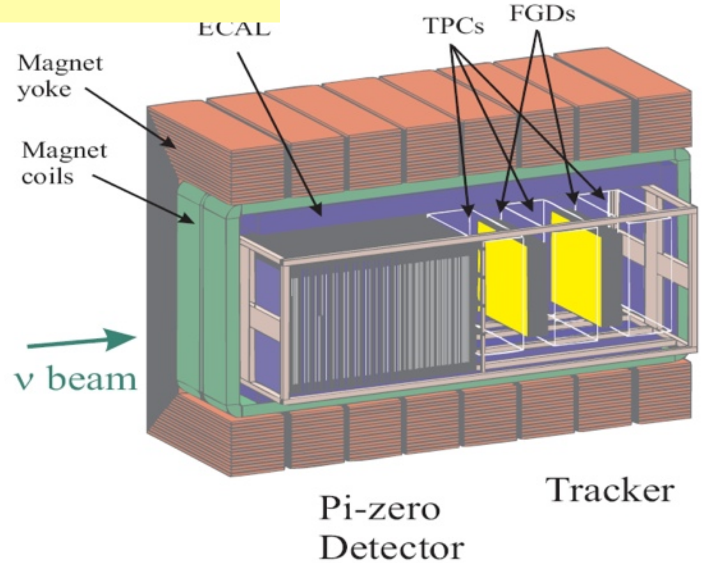
multiple detectors cancel systematics



Sampling detectors for neutrino beams

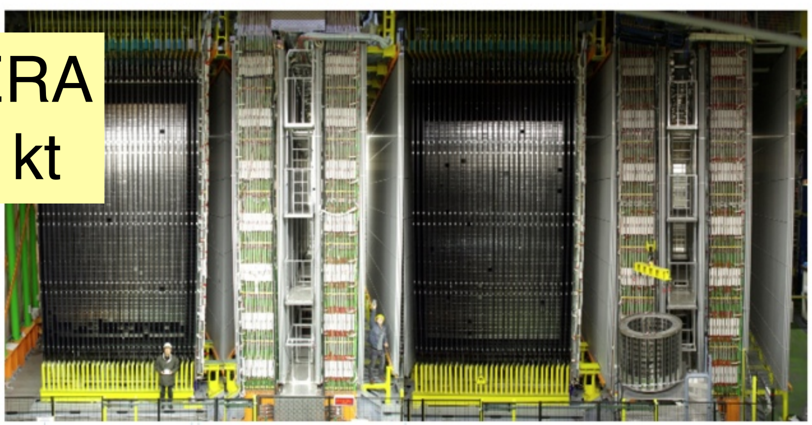
- Absorber: Pb, Fe, …
- Sensitive detectors: Emulsion Films(OPERA), Plastic(MINOS) and Liquid(NOVA) Scintillators, RPC(INO), …
- Near detector issues: hybrid detector system to monitor neutrino/muon flux & beam profile

T2K near



OPERA detector 150,000 ECC 1.25kton target
~3'100 m.w.e. overburden, ~1 cosmic μ / m² x hour

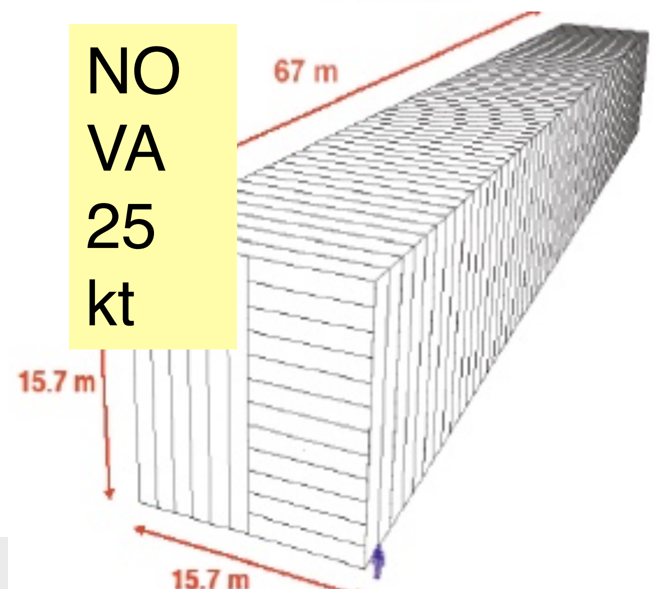
OPERA 1.25 kt



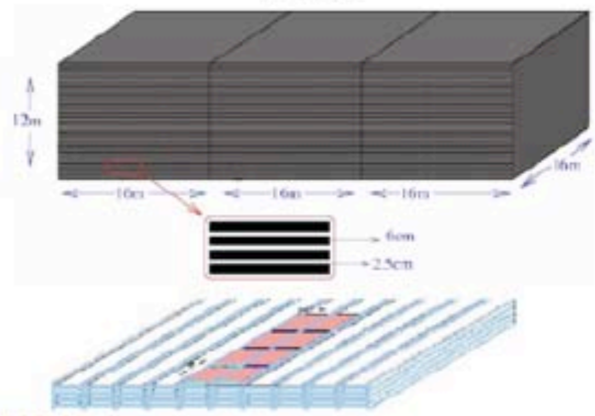
Target area

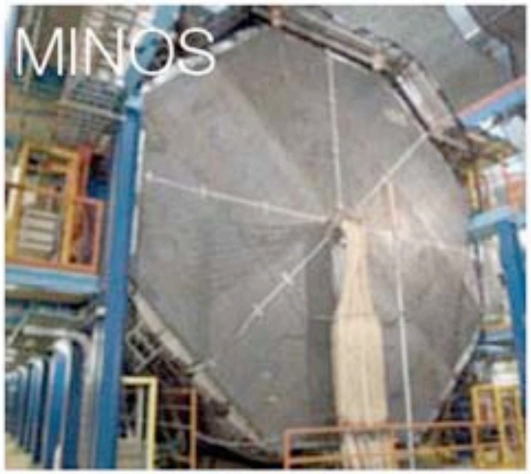
Muon spectrometer

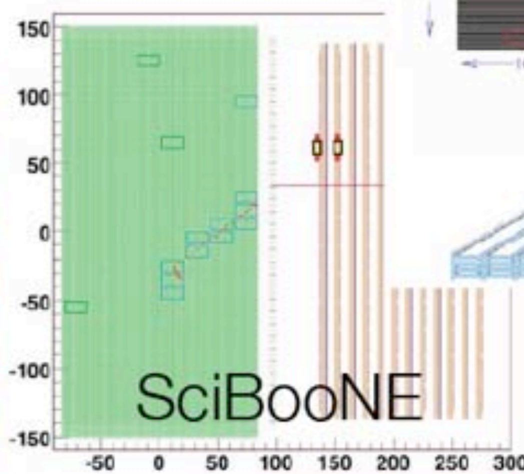
NO VA 25 kt

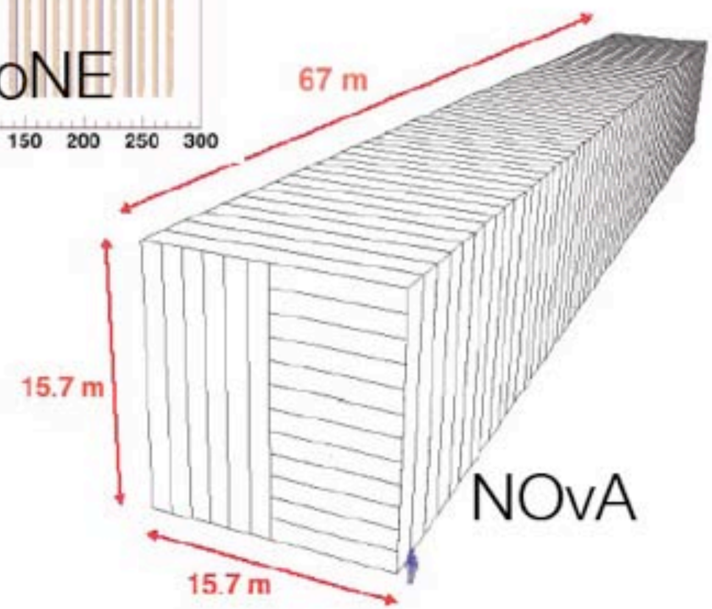


Tracking Calorimeters

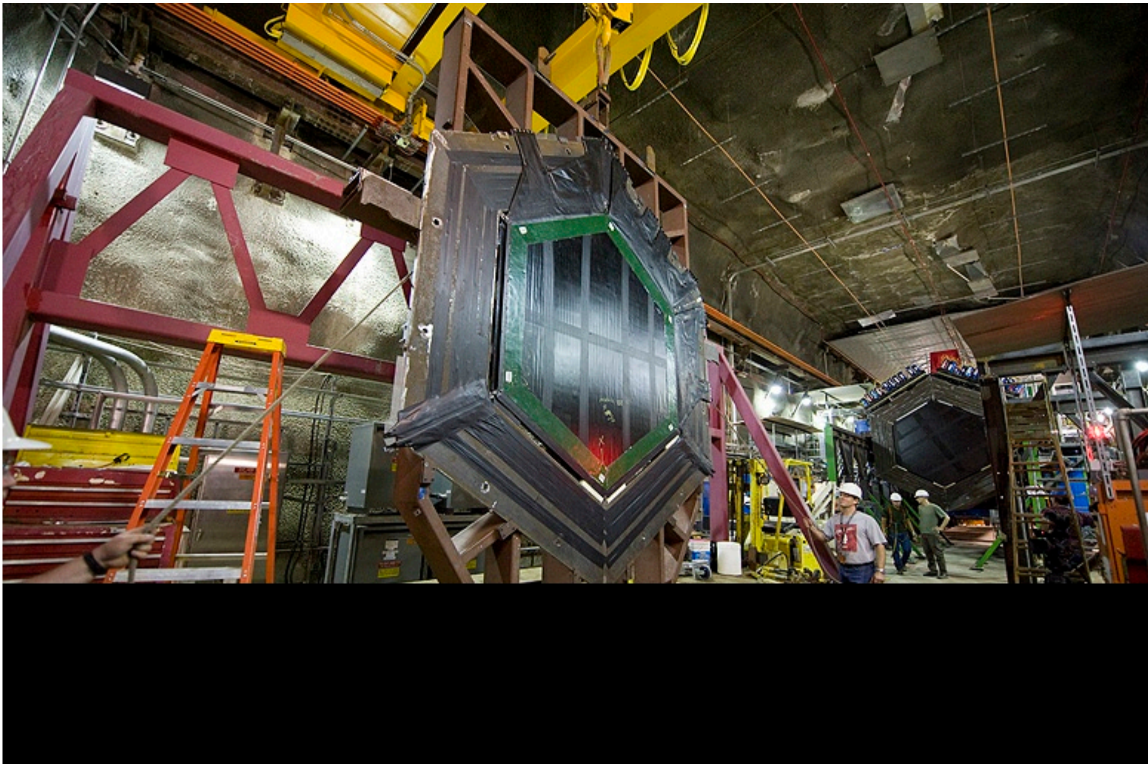


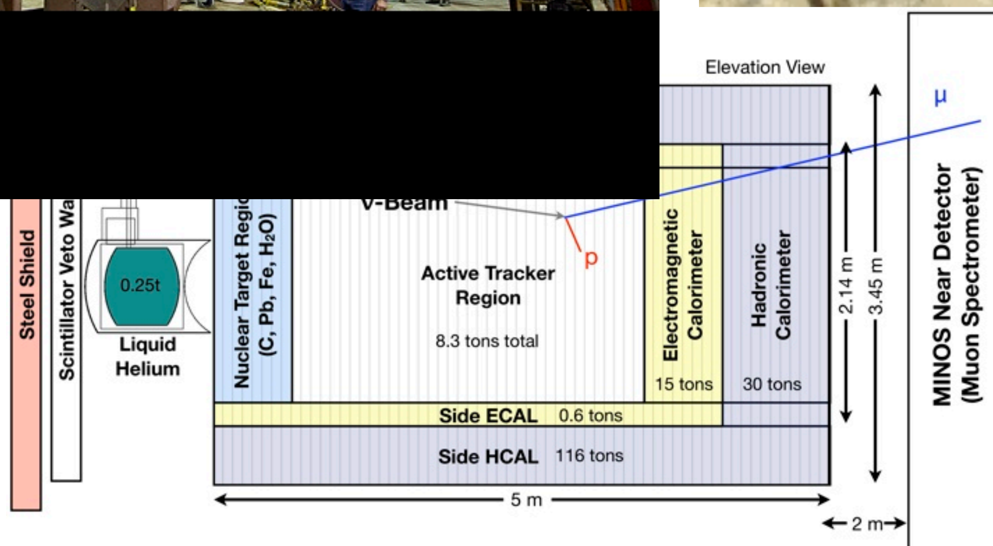






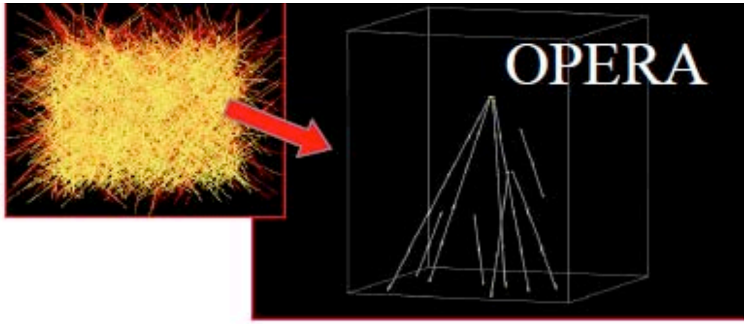
Minerva

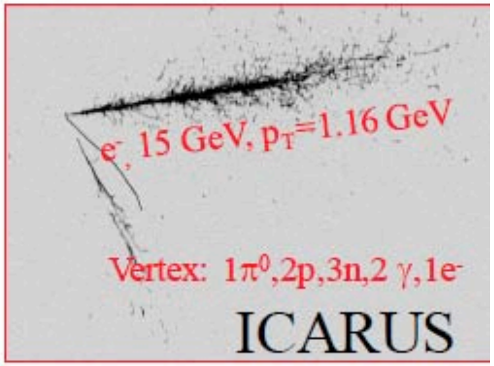


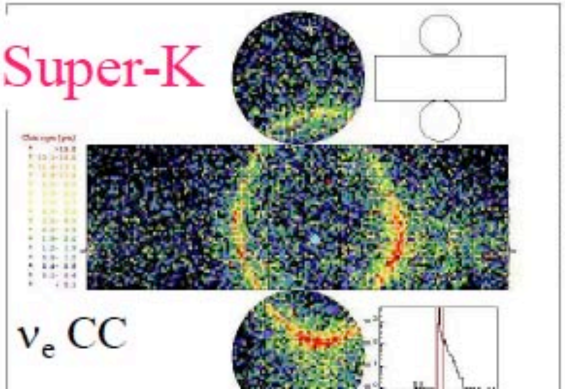

Elevation View
μ
p
Active Tracker Region
8.3 tons total
Electromagnetic Calorimeter
15 tons
Hadronic Calorimeter
30 tons
2.14 m
3.45 m
MINOS Near Detector (Muon Spectrometer)
Steel Shield
0.25t
Liquid Helium
(C, Pb, Fe, H₂O)
Side ECAL 0.6 tons
Side HCAL 116 tons
5 m
2 m

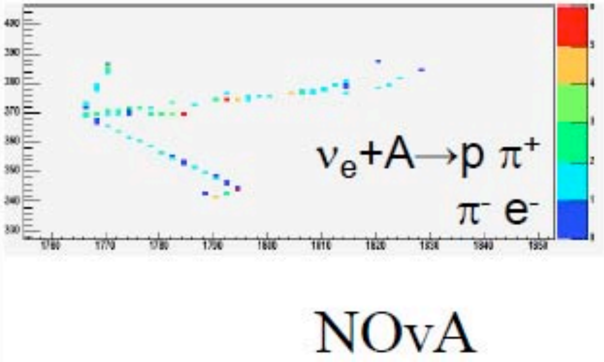
Neutrino Detectors

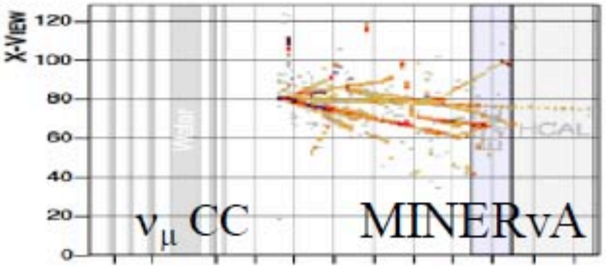
Exp't	ν Energy (GeV)	Detector Technology
MINOS	2-6	Steel Scintillator
MINERvA	1-20	Solid Scintillator
OPERA	15-25	Emulsion-Lead
ICARUS	15-25	Liquid Argon TPC
T2K	0.7	Water Cerenkov
NOvA	2	Segmented Scintillator







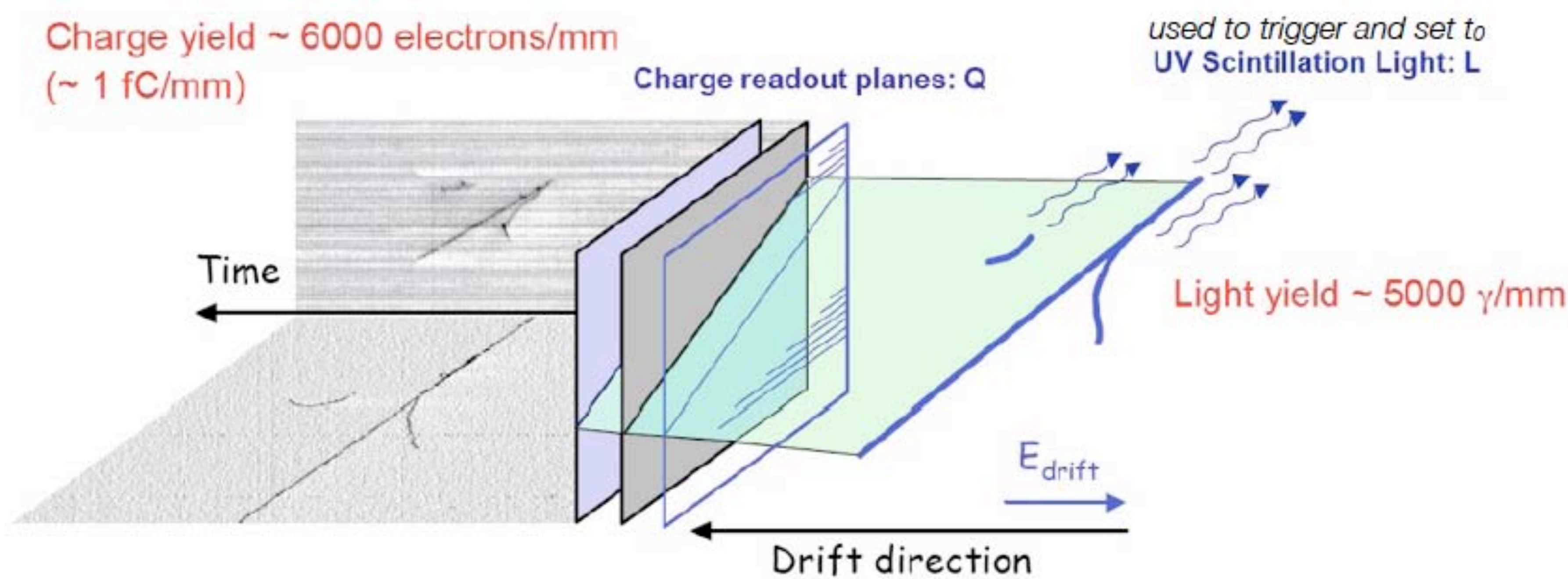




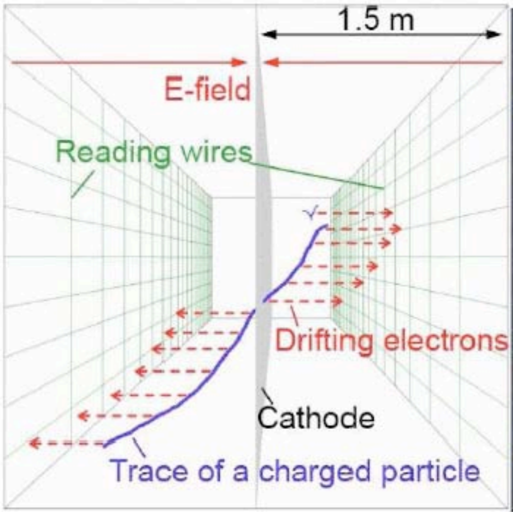
LAr TPC Concept

To be applicable to neutrino experiments higher density is required. Use liquid Ar instead of gas. Has potential to reach very large masses (100 kt) with ~mm granularity.

- Boiling point: 87 K (compare to N_2 77 K)
- Density 1.4 g/cc
- Interaction length: 114 cm
- Radiation length: 14 cm
- Moliere radius: 7 cm



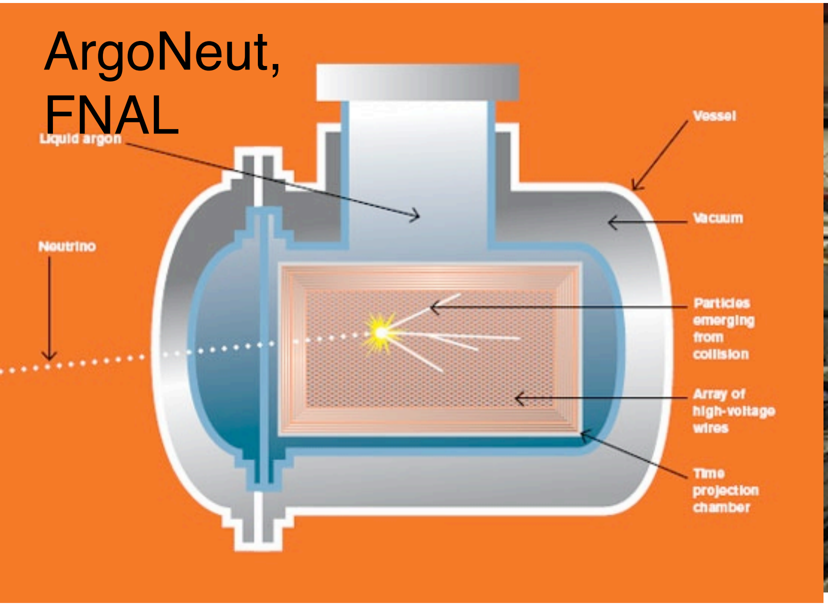
LAr Detectors

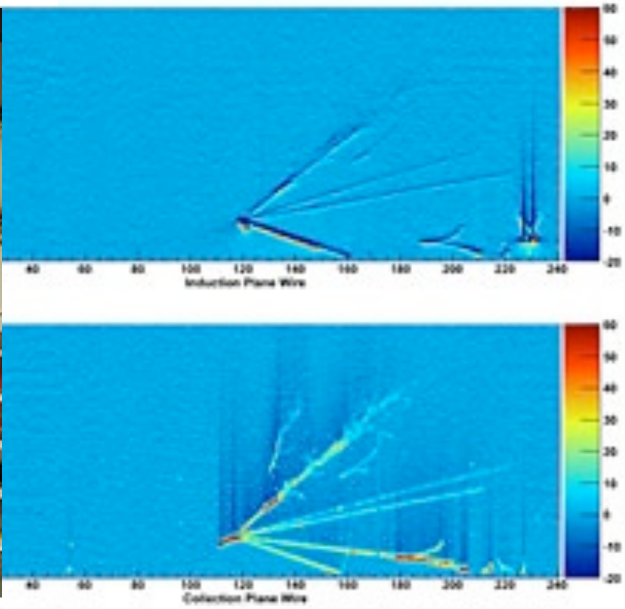


A.M. de la Ossa Romero, hep-ex/0703026

Icarus T300

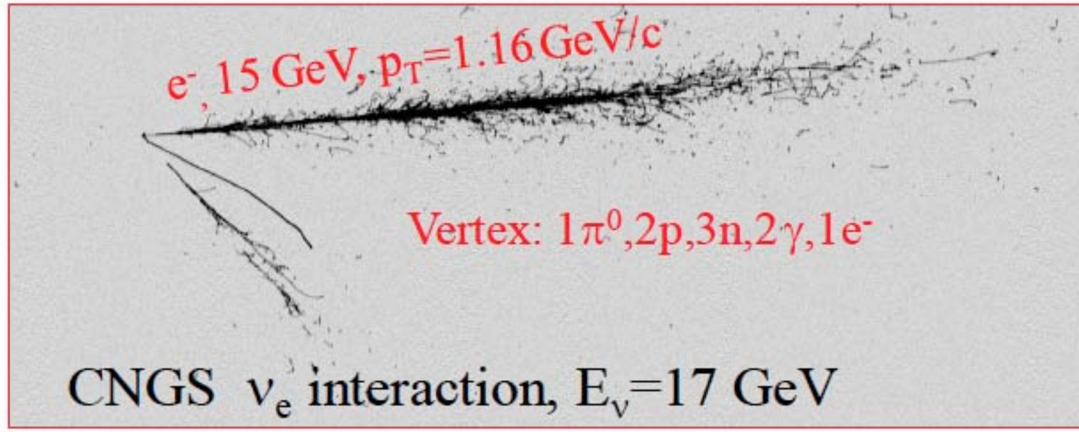
ArgoNeut, FNAL

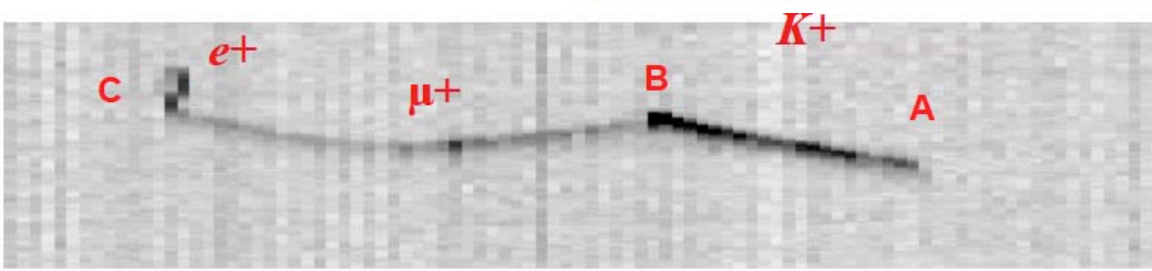




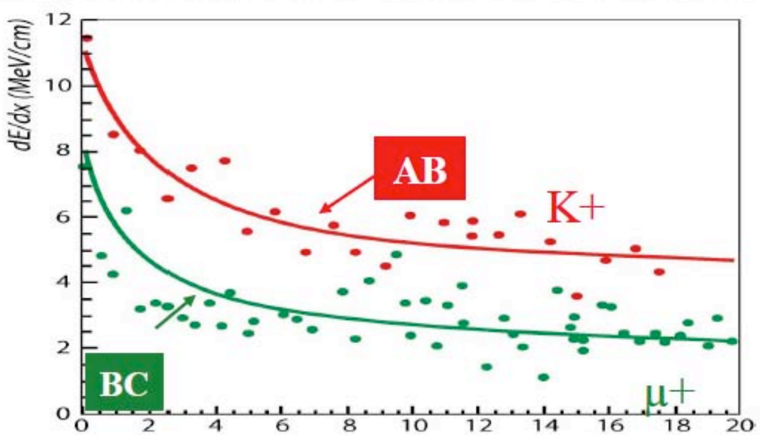
LAr Detectors - Lots of Event Information

Courtesy
André
Rubbia





Run 939 Event 46



for a single event, see dE/dx versus momentum (range)

Detector Comparison

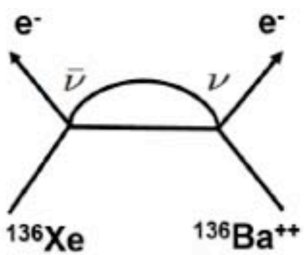
Technology Choice is a Trade-Off

Detector Technology	Largest Mass to Date (kton)	Event by Event Identification			+/-?	Ideal ν Energy Range
		ν_e	ν_μ	ν_τ		
LAR TPC	0.6	✓	✓		Not yet	huge
Water Cerenkov	50	✓	✓			<2GeV
Emulsion/Pb/Fe	0.27	✓	✓	✓		>.5GeV
Scintillator++	1 or less	✓	✓			huge
Steel/Scint.	5.4		✓		✓	>.5GeV

D. Harris

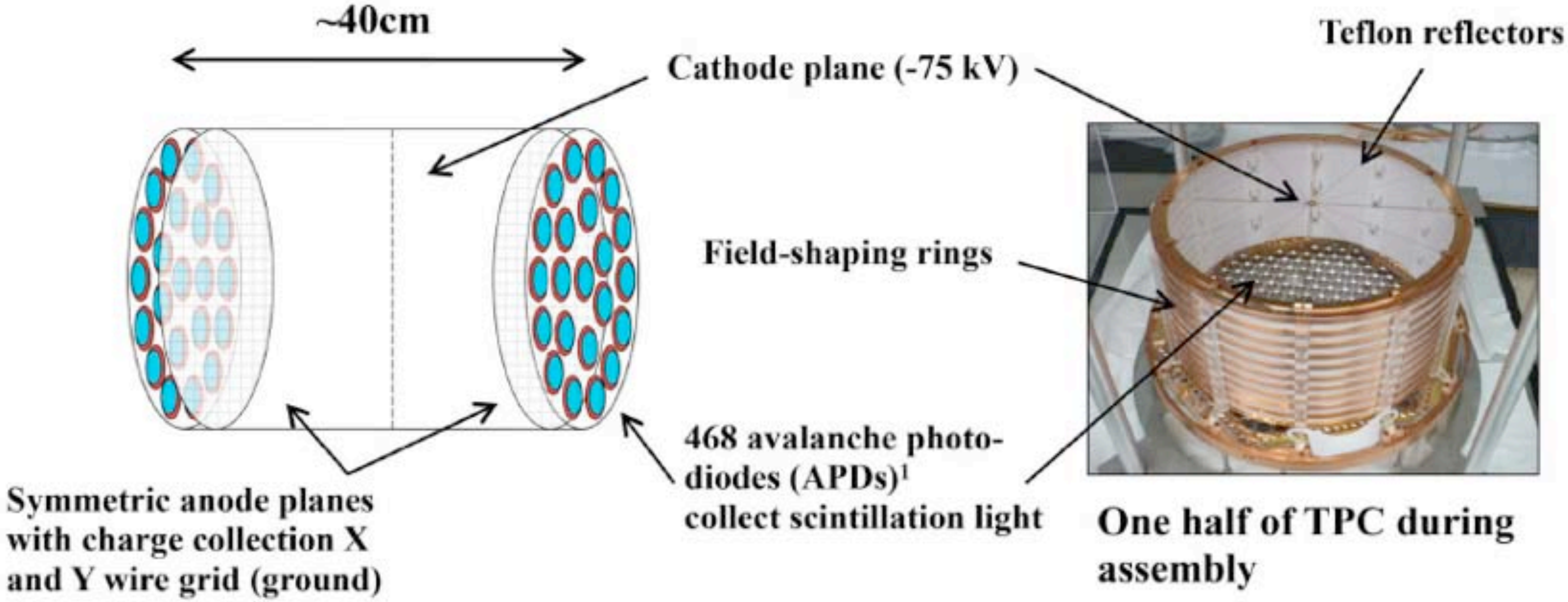
requirements for next-generation detectors
- signal efficiency
- background rejection (NC)
- probe new/other physics

EXO - Search for $0\nu\beta\beta$ in ^{136}Xe



Presently have 200 kg of 80% enriched ^{136}Xe

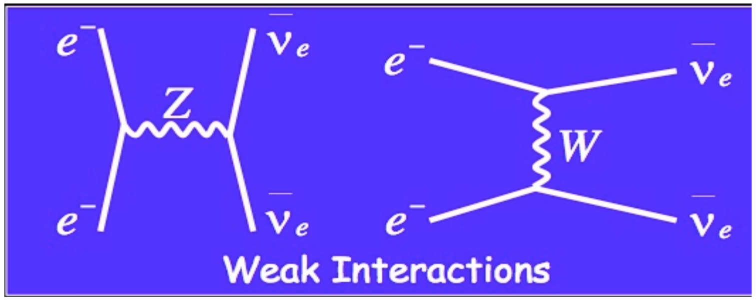
LXe TPC

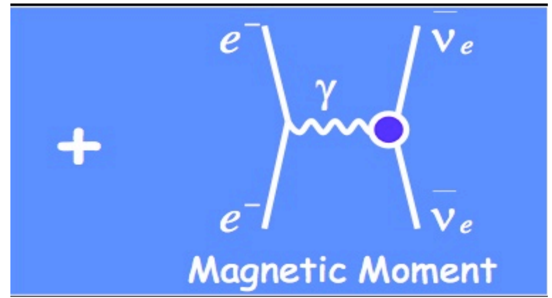


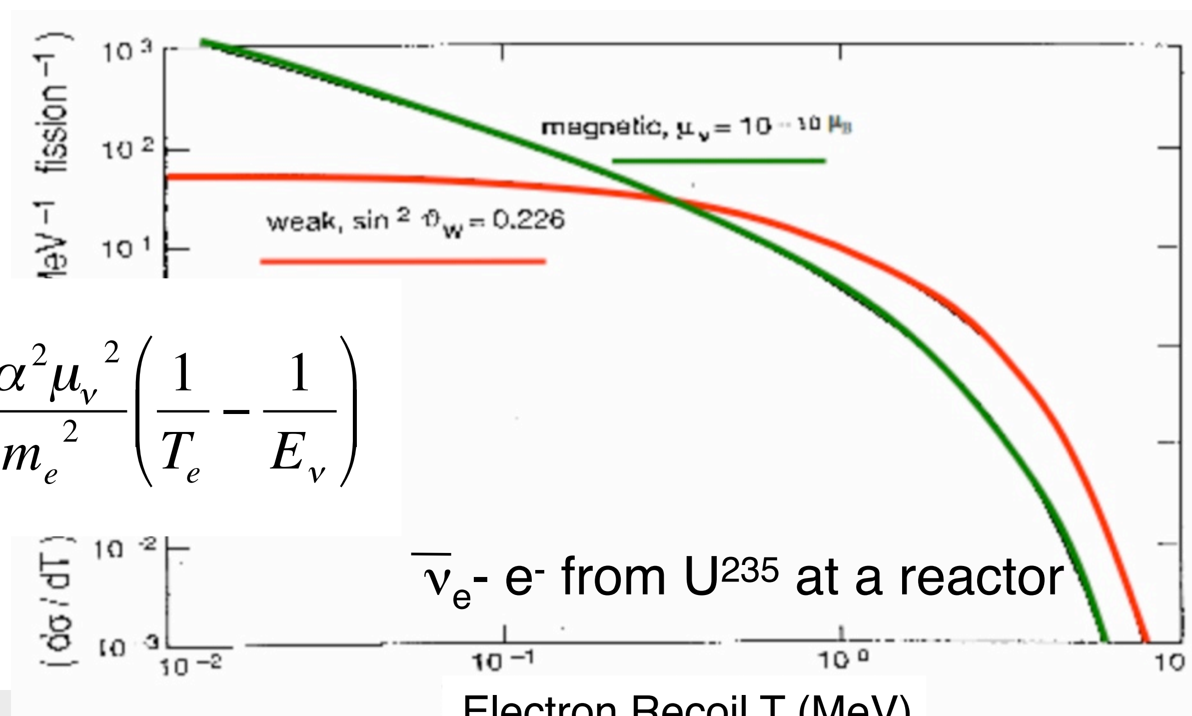
R&D on Barium tagging

TPC Experiments

What about a Neutrino Magnetic Moment?





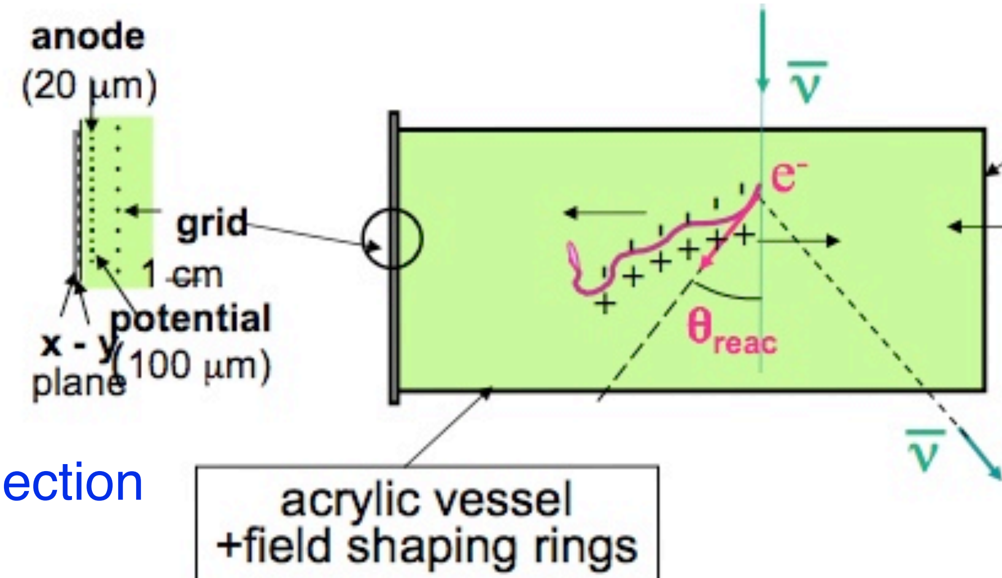


$$\frac{d\sigma}{dT_e} = weak\,\mathrm{int} + \frac{\pi\alpha^2\mu_\nu^{\ 2}}{m_e^{\ 2}}\left(\frac{1}{T_e} - \frac{1}{E_\nu}\right)$$

TPC Experiments

Low Electron Recoil Energy Experiment

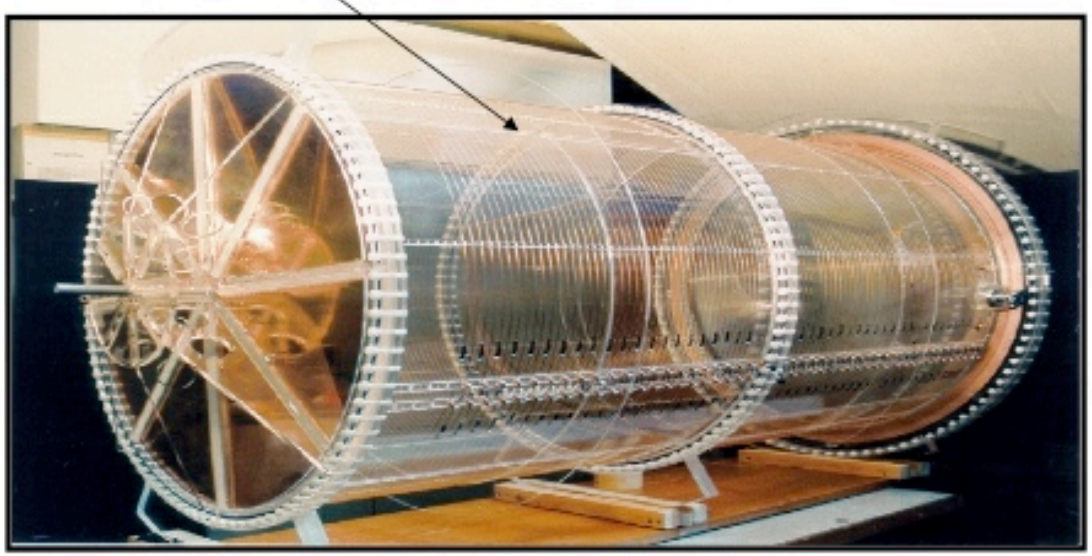
Experiment at Nuclear Reactors
(low energy source of $\overline{\nu}_e$)



3bar CF_4 gas

High density, relatively low Z, good drifting properties

Time Projection Chamber



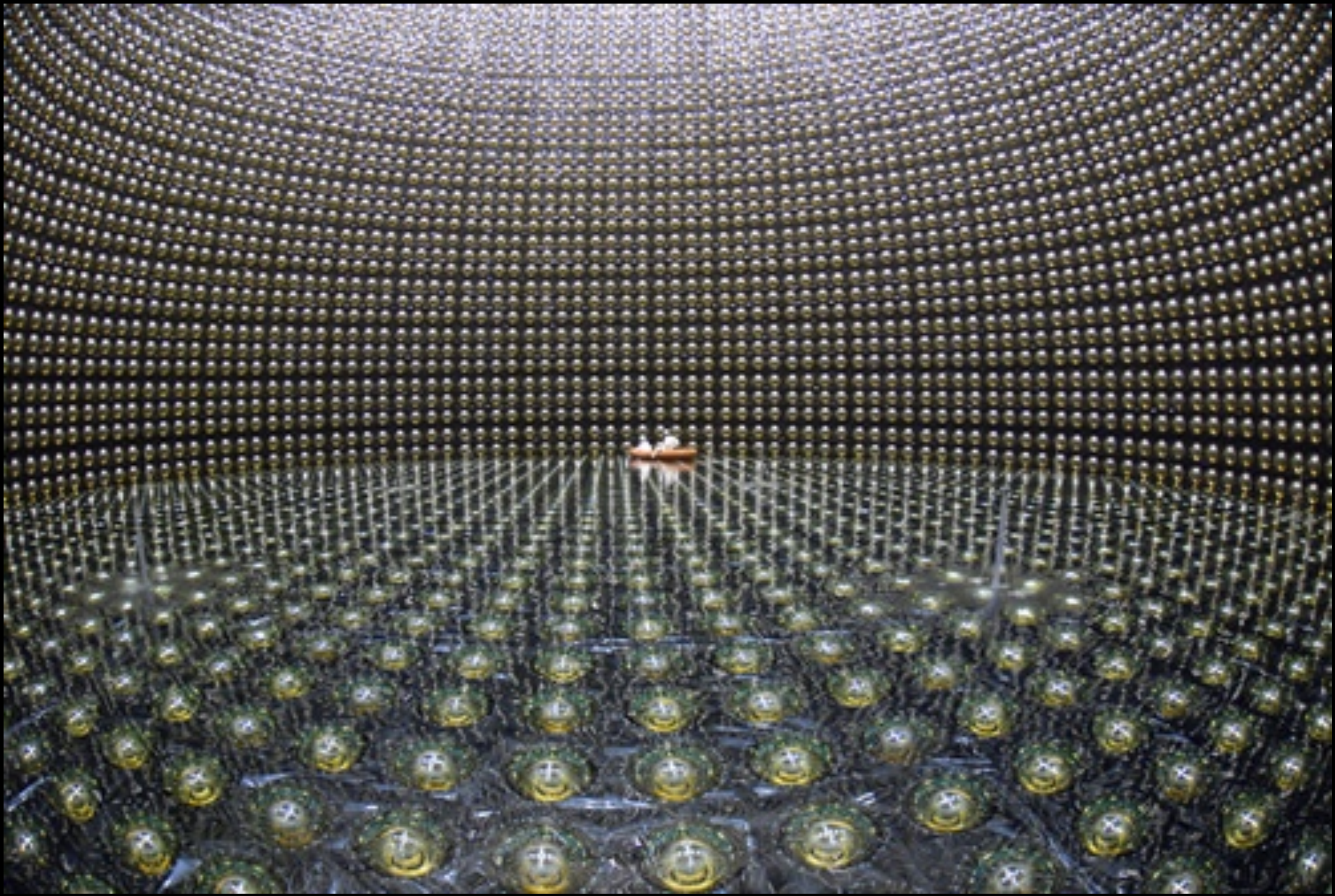
$V = 1\ m^3$

$L = 1.6\ m$

$D = 0.9\ cm$

$L = 160$ cm

$\Phi = 90$ cm



thank you